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# Test Procedure Analysis and Recommendations for Supersonic Transport Aircraft Emission Measurement

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Technical Report

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Prepared by:
Gary F. Austin

Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air and Waste Management
U.S. Environmental Protection Agency

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Determination of the emission levels from gas turbine engines operating in the afterburning mode has proven to be an extremely difficult task. This report provides analysis of two techniques for the measurement of exhaust emissions from afterburning engines, and presents the Air Force Plume Method (where emission levels are determined down stream of the exhaust where gas reactions are complete) as the preferred method. However, in limited area test environments, the Near Plume Method (where emission levels are determined at the exhaust nozzle) is an acceptable alternative of determining the emission levels from afterburning gas turbine engines.

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## Notice

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Standards Development and Support Branch
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Abstract

Determination of the emission levels from gas turbine engines operating in the afterburning mode has proven to be an extremely difficult task. The promulgated procedure for emission measurement from non-afterburning engines is not applicable because the exhaust gas reactions at the sample extraction location (the exhaust nozzle exit) are incomplete.

The Air Force Aero Propulsion Laboratory at Wright Patterson Air Force Base, Ohio recently provided a recommended procedure [1] for emission measurement from an afterburning engine through a contracted program with The General Electric Co. This recommended procedure provided two methods of constituent determination, the Far and Near Plume Methods. The Far Plume Method determines the emission levels downstream of the exhaust where the exhaust gas reactions are complete. The Near Plume Method determines the emissions level at the exhaust nozzle and through the use of a plume model the actual emission levels are determined.

This report provides analysis of two techniques for the measurement of exhaust emissions from afterburning engines and presents the Air Force Far Plume Method as the preferred method but in limited area test environments the Near Plume Method is an acceptable alternative of determining the emission levels from afterburning gas turbine engines.

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I. The Air Force Recommended Procedure

A. The Far Plume Method
B. The Near Plume Method

## 1.0 Introduction

Development of emission measurement techniques to date have been concerned with non-afterburning aircraft engines. On August 16, 1976 the EPA promulgated standards for the "Control of Air Pollution from Aircraft and Aircraft Engines, Supersonic Aircraft", 40 CFR Part 87. This document addressed the emission standards for supersonic afterburning aircraft engines but did not specify a measurement procedure.

The technique necessary for the measurement of emissions from afterburning engines differs from the non-afterburning engines only in the sample probe design, the sample extraction location and the required number of samples. For non-afterburning turbine engines, temperatures at the exhaust nozzle are typically less than 1200°F. At such temperatures, chemical reactions no longer proceed at an appreciable rate and the measured emission levels correspond to those actually ejected into the atmosphere. In the case of afterburning gas turbine engines, exhaust temperatures can reach 3500°F and chemical reactions can occur for a considerable distance downstream of the exhaust plane. To obtain the true emissions levels for afterburning turbine engines, the plume should be sampled at either a location far enough removed from the engine that the gases have been cooled to a temperature where reactions have ceased or at a location where the actual emission levels can be accurately predicted through the use of modeling techniques. The far removed procedure, however, requires a considerable clear area aft of the engine and thus would generally necessitate an outdoor test facility.

Since existing emission measurement procedures are not applicable for engines operating in the afterburning mode the Air Force undertook a contracted program to provide the definition, development, and demonstration of a emission measurement technique for afterburning engines. The result of this program is the presentation of a recommended procedure. This procedure is similar to the Society of Automotive Engineer, Aerospace Recommended Practice 1256, for the measurement of emissions from non-afterburning engines.

## 2.0 Summary and Recommendations

A. In afterburning engines the exhaust plume reaction can continue to occur at a considerable distance downstream from the nozzle exit. Exhaust gas measurements should be taken at a point far enough down stream that the reactions are complete or at a location where the actual engine emission levels can be predicted with the use of a model.

B. Pollutant constituents of concern are unburned hydrocarbons, carbon monoxide, and the oxides of nitrogen.

E. The emission measurement sampling system proposed in the Air Force procedure is basically the same as that required by the EPA in 40 CFR Part 87.

D. The calibration and instrument checks required by the Air Force Procedure are basically the same as for the EPA procedure.

E. The Far Plume Method is the most accurate of the two methods considered although it does require a large open area down stream of the engine.

F. The emission calculation procedure for the Far Plume Method consists of data verification, a test for sample representativeness, and calculation of the emission indices or the emission flow rates.

G. The Near Plume Method is an acceptable method of determining the emission levels. This method requires the use of a model to predict the actual constituent levels since the exhaust gas reactions are incomplete at the sampling point.

H. The Near Plume Method uses a computer model, "PLUMOD", to predict the emission levels. This model uses known chemical kinetic reactions and turbulent gas mixing data in its calculations.

I. Accuracy of the Near Plume Method is best at the minimum afterburning power setting and is acceptable at the maximum afterburning power setting.

J. Both methods indicated that NOx was not generated or consumed at any power setting in the afterburning exhaust plume.

The emission measurement procedure presented by the Air Force in its study of the "Development of Emissions Measurement Techniques for Afterburning Turbine Engines,"[1] should be adopted in its basic form for the measurement of exhaust emissions for commercial afterburning engines. This procedure will provide a basic emission measurement technique which with only slight modification will fulfill the requirements established by the Environmental Protection Agency for the measurement of emissions from afterburning aircraft engines.

## 3.0 Background

The pollutant constituents of concern emitted from an afterburning gas turbine engine are the same as for a non-afterbruning engine. These are unburned hydrocarbons (HC), carbon monoxide (CO), and the oxides of nitrogen (NOx) and smoke. Smoke, a carbonatious particulate, is considered an aesthetic pollutant due to its light obscuration effect on the exhaust plume.

CO and HC emissions generally are products of inefficient combustion. At high afterburning power level, where the fuel to air mixture may be greater than stoichiometric, very high levels of CO may exist. In these regions, temperatures are too high for HC to persist. The general tendency in afterburning engines, thus, is that the CO concentrations are highest in regions of highest temperatures, while both CO and HC may exist in low temperature regions.

The chemical kinetic reactions for the formation of NO are reasonably well understood and the dominant parameter in NO formation is the maximum flame temperature. Flame temperatures are much higher in the main engine burner and more NO would therefore be expected to be formed in the main burner than the afterburner. The kinetics of the NO formation process are such that there is no significant decrease in the total NOx in the afterburner. The basic reason for this is that at the lower temperatures where thermodynamic equilibrium favors a decrease in overall NO level, the kinetics are too slow to permit any appreciable change.

Smoke is predominately generated in the primary zone of the main engine combustor under very rich and high pressure conditions. Since the pressure in an afterburner is comparatively low the smoke generated is of minor significance. In fact smoke particulates can be partially consumed in the afterburner combustion process.

The exhaust plume of an afterburning engine is commonly divided into three distinct regions as shown in Figure 1. Region one consists of a turbulent mixing area where the supersonic nozzle core flow penetrates into the parallel subsonic flow originating at the exhaust nozzle. Region two is the transition region where the supersonic core flow ends and the flow field undergoes transition until at some distance downstream the fully developed plume is turbulent free (Region 3).

The reactive nature of the exhaust plume renders it impractical to make direct measurements of the exhaust gas constituents as in the non-afterburning engine (at the exhaust nozzle). This necessitates measurement of the exhaust gas constituents by either determination of the level at the exhaust nozzle and through the use of a plume model predicting the actual pollutant contribution to the environment or measuring the constituent levels downstream of the nozzle where the reactions are complete. A disadvantage of the latter method is the substantial dilution of the constituents which compromise the accuracy of the instruments due to instrument sensitivity.

## 4.0 EPA Authority and Requirements

Section 231 of the Clean Air Act directs the Administrator to "establish emission standards applicable to emissions of any air pollutant

from any class or classes of aircraft or aircraft engines which in his judgment causes or contributes to or are likely to cause or contribute to air pollution which endangers the public health or welfare."

EPA regulations for the "Control of Air Pollution from Aircraft and Aircraft Engines, Supersonic Aircraft" 40 CFR Part 87, were issued on August 16, 1976. This document established exhaust emission regulatory levels for supersonic aircraft engines. To compliment these regulatory standards an emission measurement technique must be established.

## 5.0 Air Force Recommended Procedure

The Air Force Aero Propulsion Laboratory, Wright Patterson Air Force Base Ohio, has provided a recommended procedure (Appendix) for the continuous sampling and analysis of gaseous emissions from afterburning aircraft gas turbine engines. The intent of this document is to standardize the emission test procedures and equipment necessary for measuring carbon monoxide, carbon dioxide, nitric oxide, total oxides of nitrogen, and total hydrocarbons from afterburning engines. Due to the reactive nature of the exhaust plume from afterburning engines, special procedures are necessary to assure that the measured emissions levels correspond to those actually emitted into the surrounding atmosphere. The procedure presented is comprised of two distinct parts. The Far Plume Method, Section 5.1, describes a procedure for use when exhaust gas samples are taken at axial stations far removed from the engine exhaust plane. In the case where the required test facilities are not available for use of the Far Plume procedure, an alternative procedure the Near Plume Method, Section 5.2, is given which involves sampling at the nozzle exit plane. The use of the Near Plume Method requires calculation of the actual emissions levels utilizing a computer program derived from a reactive plume analytical model.

### 5.1 The Far Plume Method

Analysis Equipment - NDIR instruments are specified for CO and $CO_2$ measurements, a flame ionization detector for HC, and a chemiluminescence analyzer with converter for NO and NOx. This follows the EPA equipment specifications (Federal Register, July 17, 1973). For the NDIR instruments, zero drift and span drift are specified at 0.5 percent for 1 hour, rather than 1 percent for 2 hours required by the EPA regulations. Repeatability and noise are specified at 0.5 percent. The sensitivity specified is 0.3 ppm and 0.005 percent for CO and $CO_2$, respectively. These latter requirements although more restrictive than the current EPA regulations are consistent with the lower concentration levels encountered with the Far Plume procedure. For the HC and NO analysers, the noise, zero drift, and span drift are as specified in the EPA procedure since the more sensitive ranges available on these instruments result in total instrument sensitivity adequate for the Far Plume procedure.

Sampling Equipment - The sample extraction probe is designed with the probe temperatures specified such as to permit either hot water or steam cooling. In order to specify sampling locations, both axial and radial, the sampling location is scaled according to the engine nozzle diameter. A minimum of 11 sampling points are required, approximately equally spaced across a diameter. This number of samples permits meaningful statistical treatment of the data. If fewer samples were extracted the results would have correspondingly reduced measurement accuracy.

Since very long sample lines would probably be involved with this procedure, no maximum sample line length is specified. The requirement for a maximum gas transport time of 10 seconds effectively limits the sample line length to a realistic value.

Equipment Layout - The equipment layout is similar to that specified in EPA regulations.

Instrument Routines - Instrument routines are similar to those specified in EPA Regulations. Checks in addition to those required by the EPA regulations are specified for zero and span drift, repeatability and noise level. Thermal converter efficiency check is as specified in the EPA procedure, but is required only monthly.

Test Procedures - Testing using this procedure is limited to wind velocities of less than 5 mph crosswind and 1 mph tailwind. The test procedures specified are otherwise similar to the EPA regulations.

Calculation of Results - CO and $CO_2$ are first corrected to true sample moisture level, in case a dryer was used. A linear fit of each pollutant versus $CO_2$ is then made by the method of least squares. If the slope of this linear fit line is greater than 10, then the corresponding correlation coefficient is required to be greater than 0.95. A value for the correlation coefficient of a line with a slope of less than 10 is not given. Emission indices are then calculated from the slope of the linear data fits. The emission flow rate (lb/hr) is then calculated from the overall engine fuel flow and the emission index. Emission standards can therefore be specified either in terms of emission indices or the total flow rate of emissions.

5.2 The Near Plume Method

Analysis Equipment - The specified equipment is basically the same as required by Far Plume Method.

Sampling Equipment - The sampling probe is required to be of the quenching type, and the pressure ratio across the orifice is required to be at least 5. Only general guidelines are given in regard to cooling

of the probe structure, the responsibility for the probe integrity therefore rests with the probe designer and operator. Total pressure measurements are required and permitted to be separated by no more than 0.3 inch from the sampling point. This permits use of a combination tip for simultaneous sampling in which the total pressure and gas sample are obtained from separate orifices.

The axial sample plane is required to lie within eight inches of the plane where the exhaust is completely expanded. A minimum of 22 sampling points are specified to lie across two diameters. The points are specified to be approximately equally spaced, and the outer most located at the edge of the exhaust stream. The edge of the exhaust stream is defined as the point where the total pressure of the outermost sampling point is between 1.05 and 1.10 times the ambient pressure.

Calculation of Results - All required calculation of results is accomplished by the plume model. Assembly of the plume model input data, however, requires some effort. The plume model is set up to accommodate 11 samples or stream tubes. A manual procedure is specified which effectively averages the data by plotting the data extracted at the 22 sample points against radial position and drawing a smooth curve through the data points. Eleven values are then selected from the smooth curve for input to the plume model. These 11 values are selected to be in centers of 11 equal areas.

The plume model computes emission levels at 0, 35, and 50 nozzle radii downstream of the exhaust nozzle. From this data it can then be determined at what axial locations the exhaust gas reactions are complete. If the plume reactions are not complete within this distance, the computer program is then rerun for an axial distance of 70 nozzle radii downstream.

The computer program calculates total gas flow and fuel flow, along with emission indices and total contaminant flow. The standard may thus be specified as either contaminant flow or emission index.

A check of data consistency or representative sampling is required. It is specified that the calculated fuel flow shall agree with the metered fuel flow within $\pm$ 15 percent.

## 6.0 System Analysis

The Far Plume Method is the preferred method of determining the exhaust gas constituent level. Even though the Far Plume Method determines the level of a dilute low concentration sample this method provides greater confidence and accuracy than the near plume method. The Near Plume Method relies upon a computer program model of the chemical gas kinetic reaction and the turbulent gas mixing to approximate the emission level from the partially reacted exhaust stream. As previously stated the chemical kinetic reactions of NO formation are reasonably

well understood with the maximum flame temperature being the dominant parameter in NO production. The chemical kinetic reactions for the formation of HC and CO are not well understood and at this time the formation trend can be predicted accurately but not the absolute magnitude.

Both the Far Plume Method and the Near Plume Method use the same basic emission measurement system which is similar to that promulgated by the EPA for non-afterburning engines. The only outstanding difference is the sampling probe. For the near plume method it must be capable of withstanding the severe environment in the afterburner flow path where local total temperatures may reach as high as 3600°F and corresponding local total pressures in the range of 30 to 40 psia. This high temperature at the exhaust plane requires a specially constructed probe capable of quenching or freezing the chemical reactions at the probe entrance. This can be done by rapid expansion of the gas to low pressure in the probe and by cooling of the probe.

## 7.0 The Near Plume Analytical Model

The analytical model of the physical and chemical processes occurring in the exhaust plume is formulated and structured from a series of computer programs. These programs were combined to form a model program "PLUMNP"(7) of the exhaust plume of an afterburning turbojet or turbofan engine. The model represents those features of the gas flow which influence the consumption of gas constituents in the exhaust such as:

The time average turbulent mixing of each element of the exhaust into the adjacent elements and the mixing of ambient air into the hot gas.

The time varying composition of the gas flow past each point in space.

The generation and decay of gas in the plume.

The consumption of gaseous contaminants by rate limited chemical reactions.

Input to the model includes data from a probe survey of the engine exhaust stream, together with properties of the fuel and ambient air and parameters of the engine cycle. Based on this input, the model predicts profiles of velocity, fuel, and contaminant concentrations at various axial locations in the plume, plus overall residual emissions indices derived from integration of these profiles.

This analytical model in its present form does a satisfactory job of predicting the consumption of emissions in the plume. The model was compared with experimental data from only turbojet afterburning engines, not mixed-flow turbofan afterburning engines. When data for turbofan

engines becomes available, the model should be verified for this type of augmentor. In contrast to some analytical modeling efforts which proceed from relatively simple models to more complex and sophisticated treatments, this model began from a very sophisticated initial structure and simplifications were incorporated as work progressed.

Accuracy of the analytical model predictions is illustrated in figures 2, 3, and 4 where the model predicts Emission Indices for Min., Mid., and Maximum Afterburning. These figures compare the emission indices calculated from the model to the actual test data. A comparison and observations concluded from the two methods are presented as follows:

Neither method indicated that NOx consumed or generated in the plume at any power setting.

Agreement between the two methods of analysis is excellent at all axial stations for the minimum afterburning power conditions.

The predicted overall residual level of HC is only about half of the measured level for mid afterburning power setting.

At the intermediate stations for the mid afterburning power setting the model predicts more rapid consumption of both CO and HC than was measured.

At the maximum afterburning power setting the model predicted quenching of the CO consumption reaction earlier than the data indicated.

The predicted HC consumption was to very low levels although not to the complete elimination as indicated by the data for the maximum afterburning power setting.

8.0 Procedure Recommendation

The basic procedure described and recommended by the Air Force, in TR-75-52[7], as a method of determining the emissions from aircraft gas turbine engines is recommended for use in determining emission levels from commercial afterburning engines. This procedure as previously described presents two techniques for emission measurement, the Near Plume Method and the Far Plume Method. The Far Plume Method is the preferred method but in limited area test environments the Near Plume Method is an acceptable alternative.

These procedures are applicable to afterburning engines operating only in the afterburning mode. The regulatory emission measurement procedure for commercial afterburning aircraft engines would also include a test procedure for afterburning engines operating in the non-afterburning mode.

References

1. Lyon, T.F., Colley, W.C., Kenworthiy, M.J., and Dahr, D.W., "Development of Emission Measurement Techniques For Afterburning Turbine Engines", USAF Aero Propulsion Laboratory, Report No. AFAPL-TR-75-52, October 1975 (2 Supplements).

Supplement 1 - Engine Emission Test Data

Supplement 2 - Afterburner Plume Computer Program Users Manual

2. Austin, G.F., "Sources of Variability and Inaccuracies in Aircraft Gas Turbine Emission Measurements" EPA, Office of Air and Water Programs, EQTD, Report No. AQ-76-02, February 1976.

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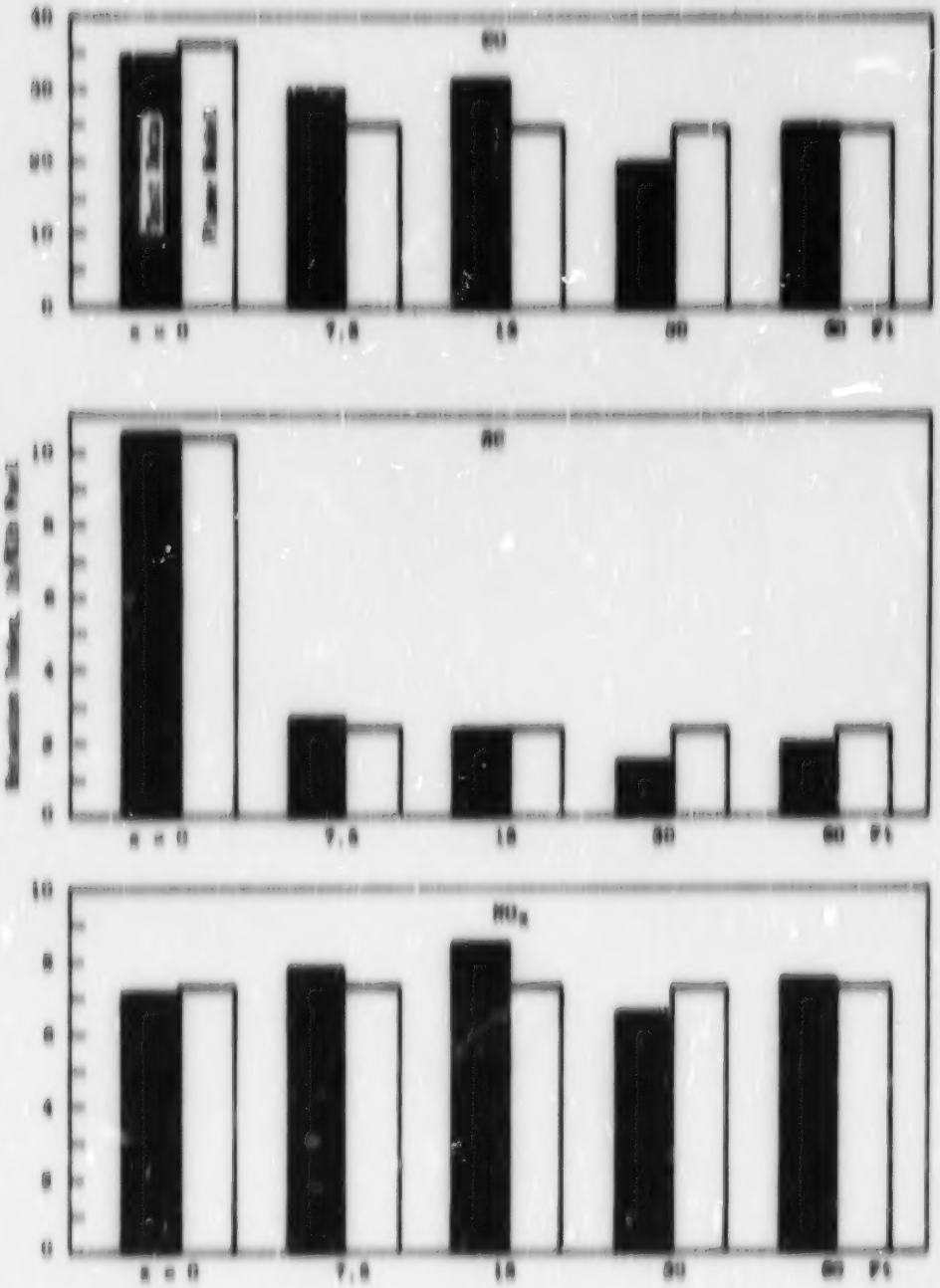



Figure 5 Plume Model Predictions of Overall Emissions Indices Compared with actual Test Data - J79-15 Engine, M=0.9, A/B.

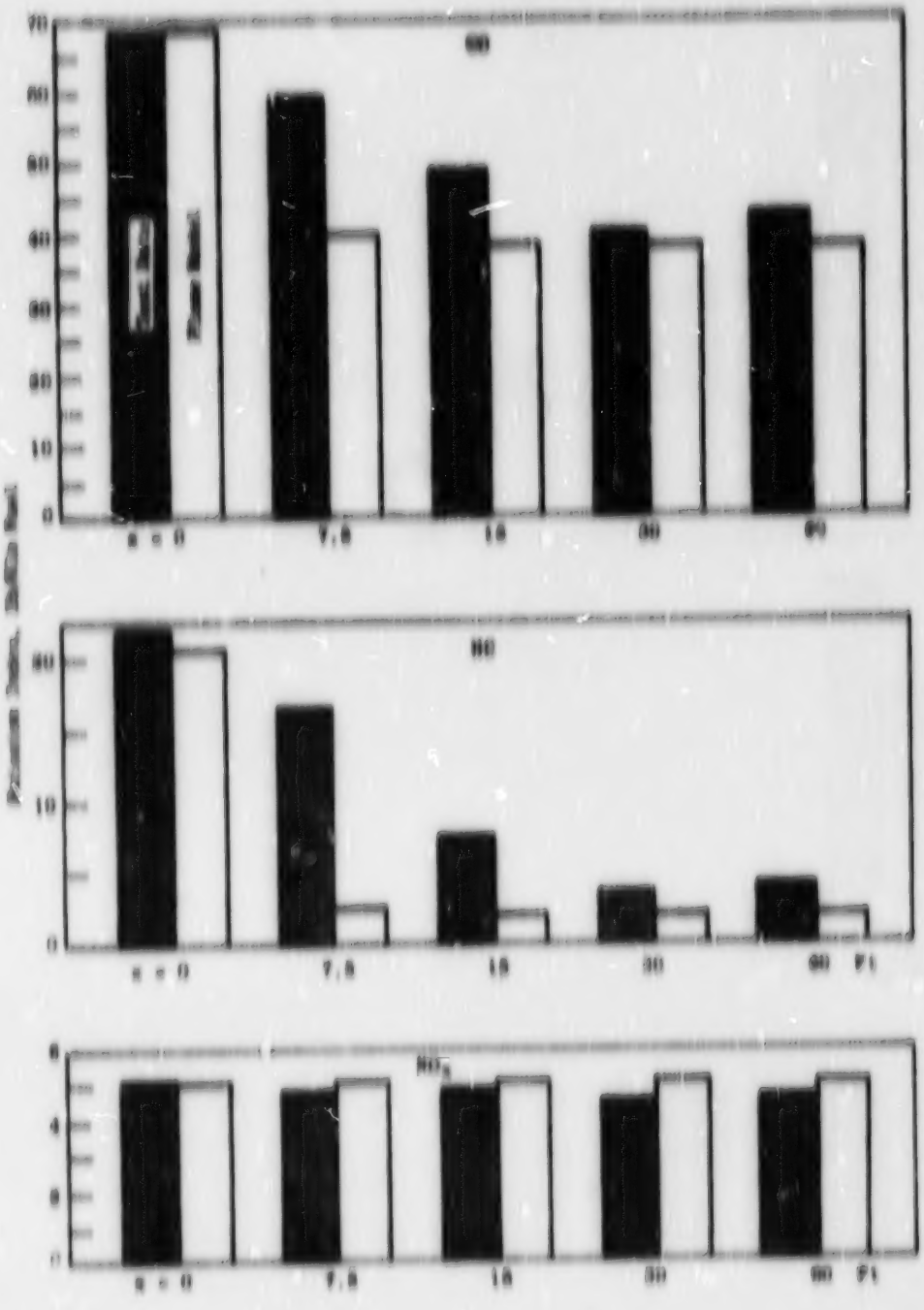


Figure 3 Plume Model Predictions of Overall Emissions Indices Compared with actual Test Data - J79-15 Engine, Mid. A/B.

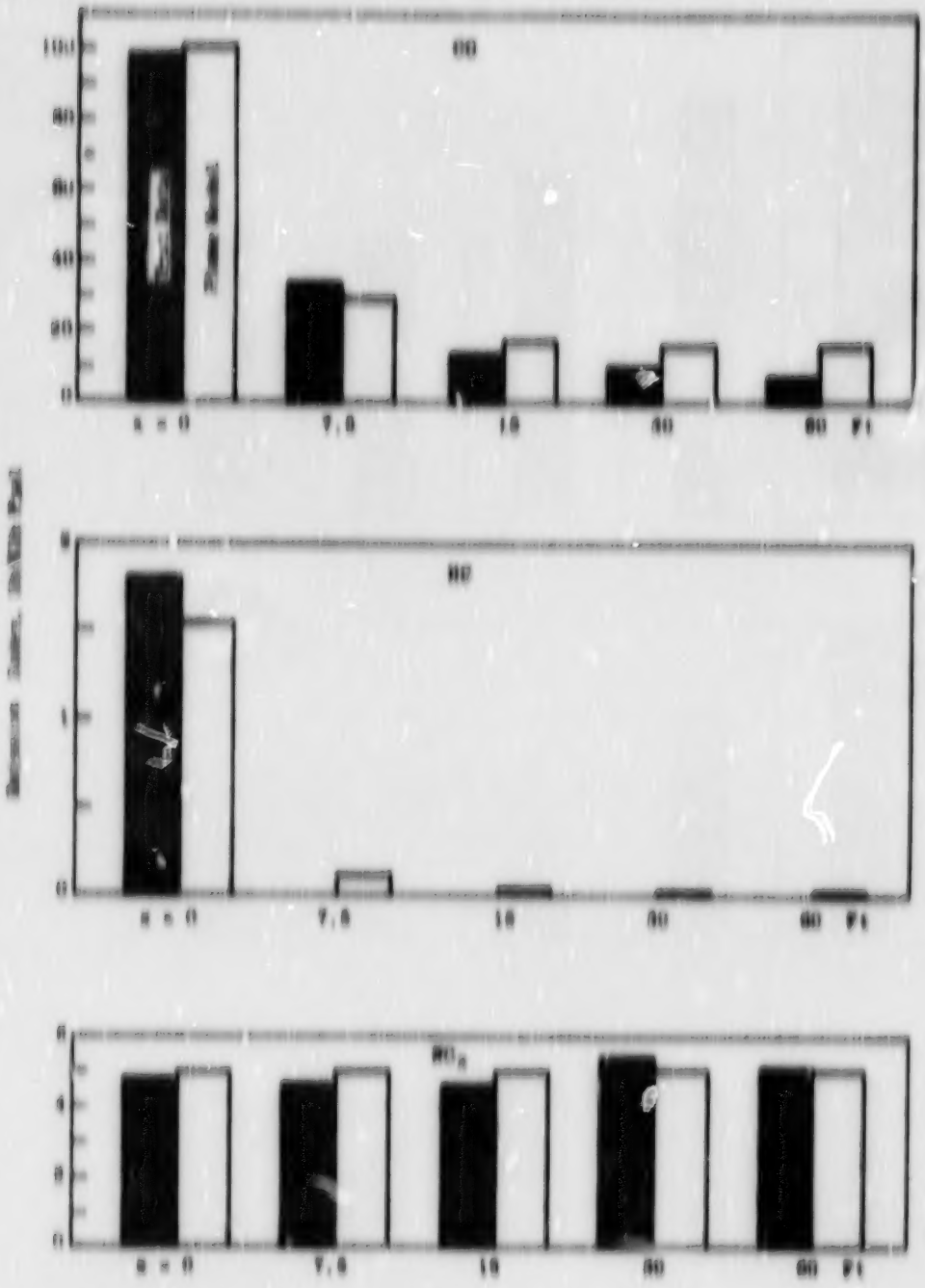


Figure 4 Plume Model Predictions of Overall Emissions Indices Compared with Actual Test Data - J79-15 Engine, Max. A/B.

## APPENDIX

Extracted From: AFAPL-TR-73-53
Development of Emissions Measurement Techniques
for Afterburning Turbine Engines
Air Force Aero Propulsion Laboratory
Wright Patterson Air Force Base, Ohio 45433

## SECTIONS

This procedure is divided into the following sections:

PART A - FAR PLUME METHOD

A1. Definitions of Terms

A2. Analysis Equipment

A3. Sampling Equipment

A4. Equipment Layout

A5. Instrument Routines

A6. Reference Gases

A7. Test Procedure

A8. Minimum Information to be Recorded

A9. Calculation of Results

PART B - NEAR PLUME METHOD

B1. Definitions of Terms

B2. Analysis Equipment

B3. Sampling Equipment

B4. Equipment Layout

B5. Instrument Routines

B6. Reference Gases

B7. Test Procedure

B8. Minimum Information to be Recorded

B9. Calculation of Results

PART A. FAR FLAME METHOD (MEASUREMENT PROCEDURE FOR SAMPLING AT AXIAL STATIONS FAR REMOVED FROM NOZZLE EXIT PLANE).

A1. DEFINITIONS

A1.1 Aircraft Gas Turbine Engine: A turboprop, turbofan, or turbo jet aircraft engine.

A1.2 Engine Exhaust: Flow of material from an engine as a result of the combustion of fuel and air.

A1.3 Exhaust Emissions: Substances ejected into the atmosphere from the exhaust discharge nozzle of an aircraft engine.

A1.4 Particulates: Solid exhaust emissions.

A1.5 Smoke: Matter in exhaust emissions which obscures light transmission.

A1.6 Augmentor: A device or method used to obtain thrust in addition to that provided by normal operation of the main engine.

A1.7 Afterburning Gas Turbine Engine: A gas turbine engine in which thrust augmentation is provided by injection and combustion of additional fuel in an afterburner. The afterburner is located between the turbine and the exhaust nozzle, the term "afterburner" generally applies to a turbojet engine. If the engine is a turbofan type, thrust augmentation may be obtained by burning in the fan stream (fanburner or ductburner) or in the combined core stream and fan stream (mixedflow augmentor).

A1.8 Pollutant: Objectionable exhaust emission.

A1.9 Plume: Region downstream of engine exhaust plane where exhaust gases mix with the ambient air.

A1.10 Total Hydrocarbons (abbreviated HC): The total of hydrocarbons of all classes and molecular weights in the engine exhaust.

A1.11 Oxides of Nitrogen (Abbreviated NOx): The total of oxides of nitrogen in the engine exhaust. The total NOx value is calculated as equivalent $NO_2$.

A1.12 Flame Ionization Detector: A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass flow rate of hydrocarbons entering the flame per unit of time, generally assumed responsive to the number of carbon atoms entering the flame.

A1.13 Nondispersive Infrared Analyzer: An instrument that selectively measures specific components by absorption of infrared energy.

A1.14 Chemiluminescence Analyzer: An instrument in which the intensity of light produced by the chemiluminescence of the reaction of nitric oxide with ozone is proportional to the concentration of nitric oxide. Conversion of $NO_2$ to NO prior to entering the analyzer permits the determination of both species.

A1.15 Interference: Instrument response due to components other than the gas that is to be measured.

A1.16 Calibration Gas: Gas of known concentration used to establish instrument response.

A1.17 Span Gas: A calibrating gas used routinely to check instrument response.

A1.18 Zero Gas: A calibrating gas used routinely to check instrument zero.

A1.19 Concentration: The volume fraction of the component of interest in the gas mixture, expressed as volume percentage or as parts per million.

## A2. ANALYSIS EQUIPMENT

A2.1 NDIR Instruments: Nondispersive infrared (NDIR) analyzer shall be used for the continuous monitoring of carbon monoxide (CO) and carbon dioxide ($CO_2$) in the turbine exhaust.

The NDIR instruments operate on the principle of differential energy absorption from parallel beams of infrared energy. The energy is transmitted to a differential detector through parallel cells, one containing a reference gas, and the other, sample gas. The detector, charged with the component to be measured, transduces the optical signal to an electric signal. The electrical signal thus generated is amplified and continuously recorded.

A2.1.1 Instrument Performance Specifications:

Response Time (electrical) - 90% full scale response in 0.5 second or less.
Zero Drift - Less than ± 0.5% of full scale in 1 hour on most sensitive range.
Span Drift - Less than ± 0.5% of full scale in 1 hour on most sensitive range.
Repeatability - Within ± 0.5% of full scale.
Noise - Less than ± 1.0% of full scale on most sensitive range.
Sample Cell Temperature - Minimum 50° C (122° F) maintained within ± 1° C (1.8° F).

A2.1.2 Range And Accuracy:

| | Range | Accuracy Excluding Interferences |
|---|---|---|
| Carbon Monoxide | 0 to 100 ppm | ± 2% of full scale |
| | 0 to 500 ppm | ± 1% of full scale |
| | 0 to 1,000 ppm | ± 1% of full scale |
| Carbon Dioxide | 0 to 1% | ± 1% of full scale |
| | 0 to 2% | ± 1% of full scale |
| | 0 to 5% | ± 1% of full scale |

A2.1.3 Sensitivity:

CO Sensitivity (on most Sensitive range) - 0.1 ppm
$CO_2$ Sensitivity (on most Sensitive range) - 0.005%

A2.1.4 NDIR Cells: All NDIR instruments shall be equipped with cells of suitable length to measure concentrations within the above ranges to the indicated accuracy. Range changes may be accomplished by use of stacked sample cells and/or changes in the electronic circuitry.

A2.1.5 Interferences: Interferences from water vapor, carbon dioxide, and carbon monoxide shall be determined on the most sensitive instrument range. Response of CO instruments shall be less than 1% of full scale for 2.5% $CO_2$ or 4% water vapor. Optical filters are the preferred method of discrimination. In some cases a cold trap or drying agent may be necessary to reduce water content below the level at which its interference is acceptable.

A2.2 Total Hydrocarbon Analyzer: The measurement of total hydrocarbon is made by an analyzer using a flame ionization detector (FID). With this type detector an ionization current, proportional to the mass rate of hydrocarbon entering a hydrogen flame is established between two electrodes. This ionization current is measured using an electrometer amplifier and is continuously recorded.

A2.2.1 General Design Specifications: The analyzer shall be fitted with a constant temperature oven housing the detector and sample handling components. It shall maintain temperature within ± 2° C of the set point, which shall be within the range 155 to 165° C (311-329° F).

The detector and sample handling components shall be suitable for continuous operation at temperatures to 200° C (393° F).

A2.2.2 Instrument Performance Specifications:

Response Time (electrical) - 90% of full scale in 0.5 second or less.
Noise - Less than ± 1.0% of full scale on most sensitive range.
Repeatability - Within ± 1.0% of full scale.
Zero Drift - Less than ± 1% of full scale in 4 hours on all ranges.
Span Drift - Less than ± 1% of full scale in 8 hours.
Linearity - Response with propane in air shall be linear within ± 2% over the range of 0 to 500 ppmC.

A2.2.3 Range and Accuracy

| Range | Accuracy |
|---|---|
| 0 to 10 ppmC | ± 5% of full scale with propane calibration gas. |
| 0 to 100 ppmC | ± 2% of full scale with propane calibration gas. |
| 0 to 500 ppmC | ± 1% of full scale with propane calibration gas. |

A2.2.4 Sensitivity

HC Sensitivity (on most sensitive range) - 0.1 ppm

A2.3 Chemiluminescence Analyser

A2.3.1 General Instrument Description: A chemiluminescence analyser with thermal converter shall be used for measuring nitric oxide (NO) and total oxides of nitrogen ($NO_x$). The chemiluminescence method utilizes the principle that NO reacts with ozone ($O_3$) to give nitrogen dioxide ($NO_2$) and oxygen ($O_2$). Approximately 10 percent of the $NO_2$ is electronically excited. The transition of excited $NO_2$ to the ground state yields a light emission (600-3000 nanometer region) at low pressures. The detectable region of this emission depends on the PM-tube/optical filter being used in the detector. The intensity of this emission is proportional to the mass flow rate of NO into the reactor. The light emission can be measured utilizing a photomultiplier tube and associated electronics.

The method also utilizes the principle that $NO_2$ thermally decomposes to NO ($2NO_2 \rightarrow 2NO + O_2$). A thermal converter unit designed to provide essentially complete conversion of $NO_2$ to NO is included as a part of the chemiluminescence analyser package. If the sample is passed through the converter prior to entering the chemiluminescence analyser, an $NO_x$ reading (NO + $NO_2$) is obtained. If the converter is bypassed, only the NO portion is indicated.

A2.3.2 Instrument Performance Specifications

Response time (electrical) - 90% of full scale in 0.3 seconds or less.
Noise - Less than 1% of full scale.
Repeatability - ± 1% of full scale.
Zero drift - Less than ± 1% of full scale in 2 hours.
Span drift - Less than ± 1% of full scale in 2 hours.
Linearity - Linear to within ± 1% of full scale on all ranges.
Accuracy - ± 1% of full scale on all ranges.

A2.3.3 Range and Accuracy

| Range | Accuracy |
|---|---|
| 0 to 10 ppm | ± 5% of full scale |
| 0 to 100 ppm | ± 2% of full scale |

A2.3.4 Sensitivity

NO sensitivity (on most sensitive range) - 0.1 ppm

## A3 SAMPLING EQUIPMENT

### A3.1 Sampling Probe:

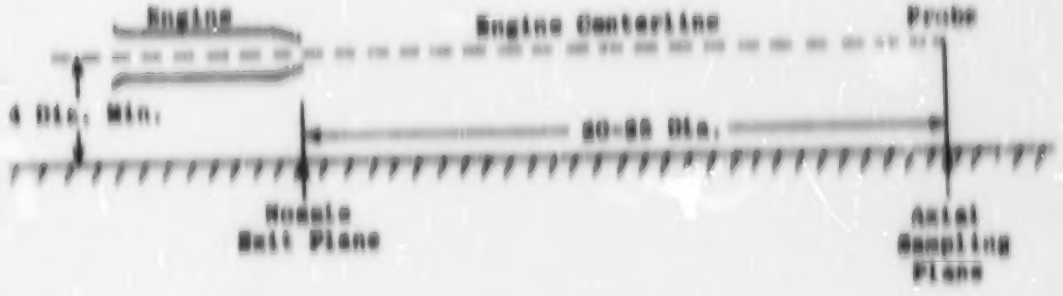
A3.1.1 Design Concept: The sampling probe shall be constructed so that individual samples may be withdrawn at various locations across a diameter of the plume. Mixed samples are not permitted. Either a single-element movable probe or a multielement rake may be used.

A3.1.2 Probe Material: The parts of the probe wetted by the sample gas shall be of stainless steel. Other materials may be used in contact with the sample gas if it is demonstrated that the material does not alter the composition of the sample.

A3.1.3 Probe Temperature: The sample line within the probe shall be maintained at a temperature between 180 and 387° F.

A3.2 Sampling Locations. Both radial and axial sampling locations depend upon the size of the engine. In order to arrive at a common dimension, referred to the particular engine to be tested, there is herein defined a nozzle exit diameter, and all sampling locations are referred to this dimension. The nozzle exit diameter is for the maximum engine power condition and either may be obtained by actual measurement or may be calculated from engine operating conditions. The calculated nozzle exit diameter is obtained by complete expansion of the total engine flow to ambient pressure at the maximum power condition.

A3.2.1 Axial Sampling Station. The axial sampling plane shall be no less than 20 nor more than 35 nozzle exit diameters from the nozzle exit plane as shown below. At this sampling plane, there shall be an unobstructed area at least four nozzle exit diameters in radial distance about the projected engine centerline. (See sketch below.)



A3.2.2 Radial Sampling Locations. A minimum of 11 sampling points shall be used. These sampling points should be approximately equally spaced across the plume diameter, with one sample located on the plume centerline. If the sampling system is such that the sampling points cannot lie in a straight line (across a diameter), then a minimum of five samples shall be taken in each of two opposite sampling quadrants, with one sample taken at the plume centerline.

The outermost sampling points shall be at least four but no more than five exit nozzle diameters from the plume centerline. The sample at the center of the plume shall be taken at a distance no greater than 0.6 exit nozzle diameters from the true projected engine centerline

A3.3 Sample Transfer. The sample shall be transferred from the probe to the analytical instruments through a heated sample line of either stainless steel or Teflon of 0.18 to 0.35-inch ID. The sample line shall be maintained at a temperature of 300 ± 27° F.

Sample line length should be as short as possible, consistent with the test setup. Suitable noncontaminating sample pumps are required to maintain the proper sample flow rate and to provide adequate sample pressure at the instruments. The total sample flow rate shall be such that the sample gas is transported from the probe inlet to the analyser inlet in less than 10 seconds.

A4. EQUIPMENT LAYOUT

A schematic diagram of the emissions measuring system is shown in Figure B1. Additional components such as instruments, thermocouples, valves, solenoids, pumps, and switches may be used to provide additional information and coordinate the functions of the component systems. Parallel installation of CO and $CO_2$ analysers is an acceptable alternative. No desiccants, dryers, water traps or related equipment may be used to treat the sample flowing to the $NO_x$ analyser. The $NO_x$ instrument configuration must be such that water condensation is avoided throughout the instrument.

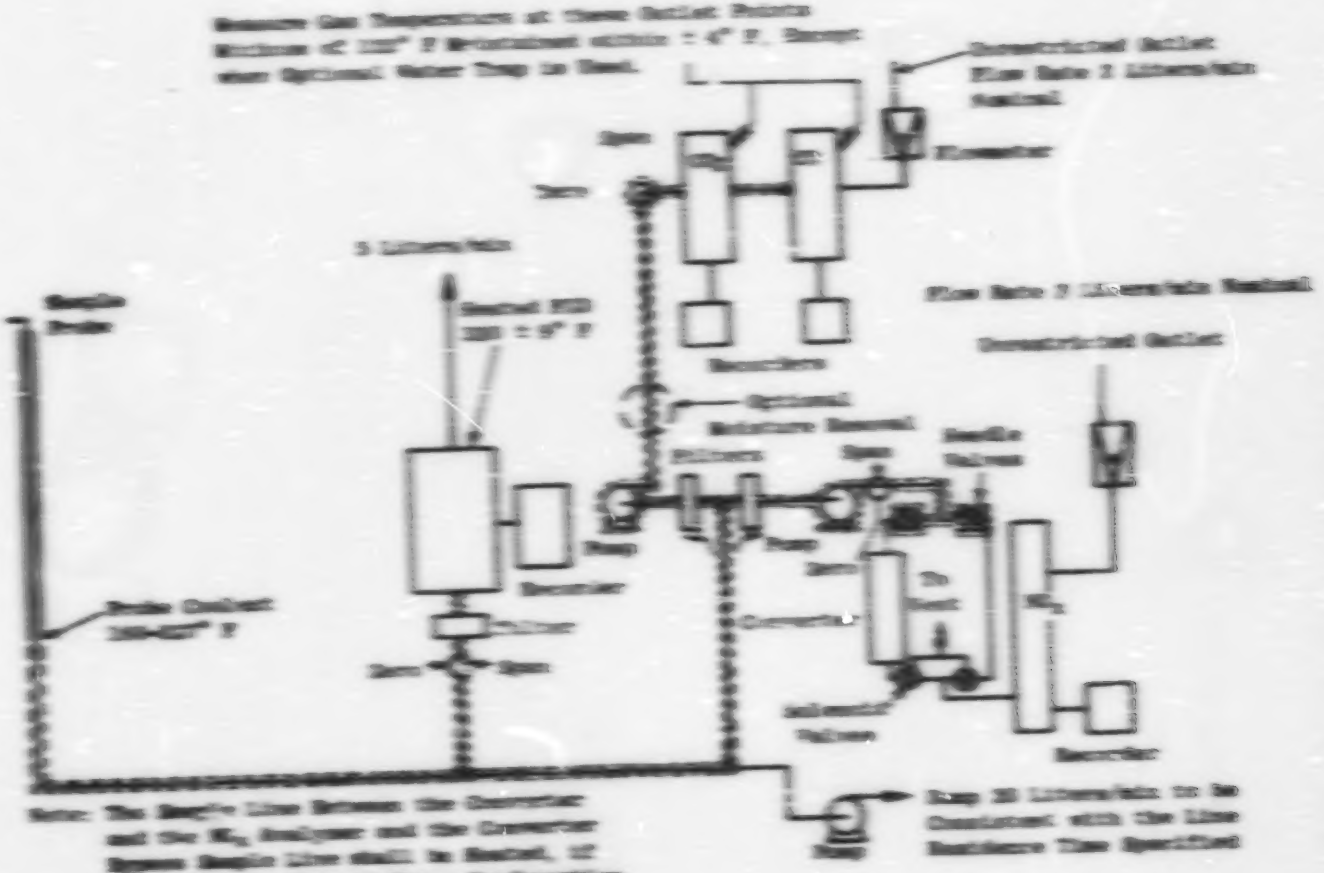


Figure 11. Sampling System Schematic.

A5. INSTRUMENT ROUTINES

A5.1 NDIR Instruments: Following the instrument manufacturer's instructions for startup of instruments, the following minimum requirements shall be adhered to:

A5.1.1 Monthly Routine:

(1) Check detector tuning, following manufacturer's prescribed routine.

(2) Set instrument zero using dry nitrogen.

(3) Using previous gain setting check calibration curves using calibration gas with nominal concentrations of 30, 60, and 90% of each range used. Use the same gas flow rate through instruments during calibration as when sampling exhaust. Any response value differing from the previous value by more than ± 3% of the previous value at the same gain setting may reflect some problem in the instrument system, and a thorough instrument check should be made. Confirm or reestablish calibration curves for each range. Log gain reading.

(4) Check response of interference gases as called out in A2.1.4. If unacceptable, determine cause and correct -- detector replacement may be indicated.

(5) Prior to each testing period, a check of the instrument zero and span drift, repeatability and noise level shall be made on the most sensitive instrument range to insure that it conforms with the instrument performance specifications.

A5.1.2 Daily Routine:

(1) If analyser power is not left on continuously, allow 2 hours for warmup. (If daily use is anticipated, it is recommended that analyser be left on continuously.)

(2) Replace or clean filters.

(3) Check system for leaks.

(4) Check detector tuning and record reading. If the reading changes by more than ± 3% from the previous value, instrument readjustment is indicated. For the following tests the temperature of zero and span gas in the instrument cell's shall be within ± 2° C (± 3.6° F) of typical sample gas temperature

measured at the outlet of the sample cell, and gas flow rate through the instruments shall be the same for zero and span gas as for sample gas.

(5) Zero the instrument on dry nitrogen. If there is a significant change in setting of zero control, determine the cause and correct.

(6) Using span gas to give 75 to 90% full-scale deflection, check the response of the instrument on each range using the gain setting from the previous use. If the reading differs from the previous value by more than 3%, an instrument problem may be indicated. Check and correct as necessary. If instrument reading is within ± 3% of previous value, adjust gain control to produce proper instrument output. Log gain setting at final adjustment.

(7) Check zero with dry nitrogen and repeat step 6 if necessary.

(8) Zero and span shall be checked before and after each test, and at approximately one-hour intervals during the test.

A5.2 Total Hydrocarbon Analyzer

A5.2.1 Initial Alignment:

A5.2.1.1 Optimization of Detector Response:

(1) Follow manufacturer's instructions for instrument startup and basic operating adjustment. Fuel shall be 60% helium, 40% hydrogen containing less than 0.1 ppmC hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 0.1 ppmC.

(2) Set oven temperature at 160° C ± 5° C (320° F ± 9° F) and allow at least one-half hour after oven reaches temperature for the system to equilibrate. The temperature is to be maintained at set point ± 2° C (± 3.5° F).

(3) Introduce a mixture of propane in air at a propane concentration of about 500 ppmC. Vary the fuel flow to burner and determine the peak response. A change in zero may result from a change in fuel flow; therefore, the instrument zero should be checked at each fuel flow rate. Select an operating flow rate that will give near maximum response and the least variation in response with minor fuel flow variations.

(4) To determine the optimum airflow, use fuel flow setting determined above and vary airflow. A typical curve for response versus airflow is shown below:

After the optimum flow settings have been determined, these flows are to be measured and recorded for future reference.

A5.2.1.3 Oxygen Effect: Check the response of the detector with varied concentrations of oxygen in the sample following steps outlined below; this test shall be made with oven temperature at the set point and with gas flow to the detector at optimum conditions, as determined in A5.2.1.1.

(1) Introduce nitrogen ($N_2$) zero gas and zero analyser; check zero using hydrocarbon-free air; the zero should be the same.

(2) The following blends of propane shall be used to determine the effect of oxygen ($O_2$) in the sample:

Propane in $N_2$

Propane in 90% $N_2$ + 10% $O_2$

Propane in air

The volume concentration of propane in the mixture reaching the detector should be about 500 ppmC, and the concentration of both the $O_2$ and hydrocarbon should be known within ± 1% of the absolute value. The zero should be checked after each mixture is measured. If the zero has changed, then the test shall be repeated.

The response to propane in air shall not differ by more than 3% from the response to propane in the 10%-$O_2$/90%-$N_2$ mixture, nor differ by more than 5% from the response to propane in nitrogen.

If these specifications cannot be met by changing the sample flow rate or burner parameters, such as airflow and/or fuel flow rate, it is recommended that the detector be replaced.

A5.2.1.3 Linearity and Relative Response:

(1) With analyser optimized per A5.2.1.1, the instrument linearity shall be checked for the range 0 to 100 and 0 to 500 ppmC in air at nominal concentrations of 50 and 95% full scale of each range. The deviation of a best fit curve from a least-squares best-fit straight line should not exceed 2% of the value at any point. If this specification is met, concentration values may be calculated by use of a single calibration factor. If the deviation exceeds 2% at any point, concentration values shall be read from a calibration curve prepared during this alignment procedure.

(2) A comparison of response to the different classes of compounds shall be made using (individually) propylene, toluene, and n-hexane, each at 20 to 50 ppmC concentration in nitrogen. If the response to any one differs by more than 5% from the average of the three, check instrument operating parameters. Reducing sample flow rate improves uniformity of response.

A5.2.2 Routine At Three-Month Intervals: These checks are to be made at three-month intervals or more frequently should there by any question regarding the accuracy of the hydrocarbon measurements:

(1) Check for and correct any leaks in system.

(2) Check and optimize burner flows (air, fuel, and sample) as required by criteria of A5.2.1.1.

(3) Check $O_2$ effect as outlined in A5.2.1.2.

(4) Check response of propylene, toluene, and n-hexane as outlined in A5.2.1.3.

(5) Check linearity as outlined in A5.2.1.3.

(6) Prior to each testing period, a check of the instrument zero and span drift, repeatability, and noise level shall be made on the most sensitive instrument range to insure that it conforms with the instrument performance specifications. Zero instability may be caused by HC condensation in the zero gas cylinder. A molecular sieve trap has been found effective in removing HC from the zero gas.

A5.2.3 Daily Routine

(1) Clean or replace filters.

(2) Check instrument for leaks.

(3) Check instrument temperatures.

(4) Ascertain that all flows to detector are correct.

(5) Check zero with zero gas.

(6) The response using blends of propane in air shall be checked on each range:

| For range | Use |
|---|---|
| 0 to 10 ppmC | 7 to 10 ppmC propane in air |
| 0 to 100 ppmC | 70 to 100 ppmC propane in air |
| 0 to 500 ppmC | 350 to 500 ppmC propane in air |

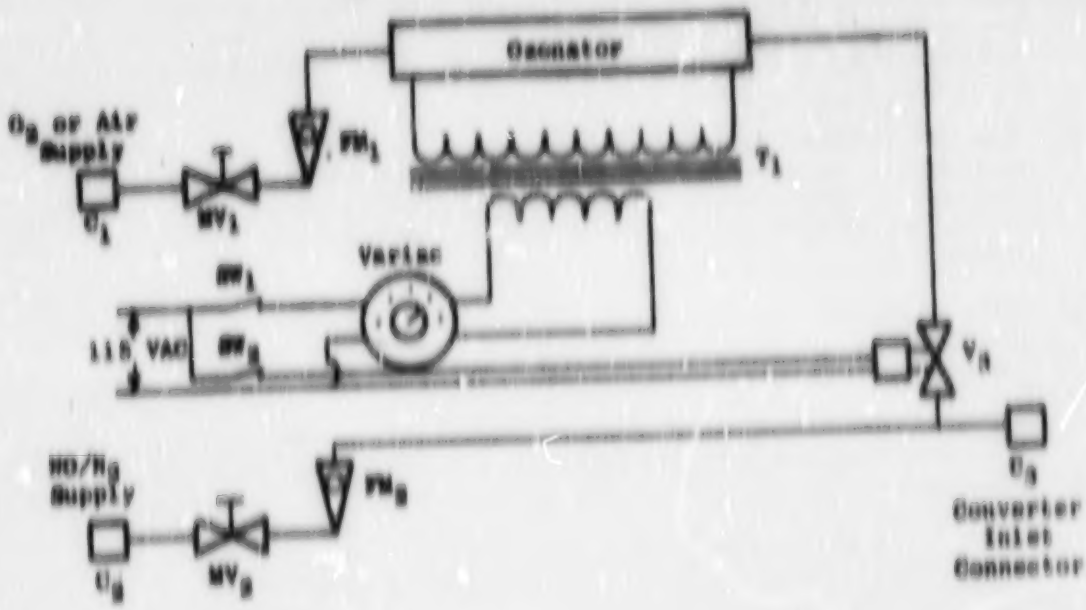
If the response differs from the last previous check value by more than 3% of the value logged during the last prior day's use, an instrument problem may be indicated.

A zero and span gas check shall be made before and after each test and at approximately one-hour intervals during the test. If the cumulative changes exceed 3% during the day, an instrument problem may be indicated.

A5.3 Chemiluminescence Analyzer: Follow the instrument manufacturer's instructions for startup of instrument.

A5.3.1 Thermal Converter Efficiency Check: Check the $NO_2$ to NO converter efficiency by the following procedure. Use the apparatus described and illustrated below:

$NO_2$ Converter Efficiency Detector




(a) Attach the NO/$N_2$ supply (75-100 ppm) at $O_2$, the $O_2$ supply at $O_1$, and the analyser inlet connection to the efficiency detector at $O_3$. If lower concentrations of NO are used, air may be used in place of $O_2$ to facilitate better control of the $NO_2$ generated during step (d).

(b) With the efficiency detector variac off, place the $NO_2$ converter in bypass mode and close valve V2. Open valve MV2 until sufficient flow and stable readings are obtained at the analyser. Zero and span the analyser output to indicate the value of the NO concentration being used. Record this concentration.

(c) Open valve V2 (on/off flow control solenoid valve for $O_2$) and adjust valve MV1 ($O_2$ supply metering valve) to blend enough $O_2$ to lower the NO concentration (b) about 10%. Record this concentration.

(d) Turn on the ozonator and increase its supply voltage until the NO concentration of (c) is reduced to about 20% of (b). $NO_2$ is now being formed from the $NO+O_3$ reaction. There must always be at least 10% unreacted NO at this point. Record this concentration.

(e) When a stable reading has been obtained from (d), place the $NO_x$ converter in the convert mode. The analyser will now indicate the total $NO_x$ concentration. Record this concentration.

(f) Turn off the ozonator and allow the analyser reading to stabilise. The mixture $NO+O_2$ is still passing through the converter. This reading is the total $NO_x$ concentration of the dilute NO span gas used at step (c). Record this concentration.

(g) Close valve V1. The NO concentration should be equal to or greater than the reading of (d) indicating whether the NO contains any $NO_2$.

Calculate the efficiency of the $NO_x$ converter by substituting the concentrations obtained during the test into the following equation.

$$\% \text{ Eff.} = \frac{(e) - (d)}{(f) - (d)} \times 100\%$$

The efficiency of the converter should be greater than 90 percent. Adjusting the converter temperature may be needed to maximise the efficiency.

(h) If the converter efficiency is not greater than 90 percent, the cause of the inefficiency shall be determined and corrected before the instrument is used.

(i) The converter efficiency shall be checked at least monthly.

A5.3.3 Monthly Routine

(i) Adjust analyser to optimise performance.

(ii) Set instrument zero using zero grade nitrogen.

(iii) Calibrate the $NO_x$ analyser with nitric oxide (nitrogen diluent) gases having nominal concentrations of 90 and 95% of full scale on each range used. Use the same gas flow rate through the instrument during calibration as when sampling exhaust. Log zero and gain settings.

(4) Prior to each testing period, a check of the instrument zero and span drift, repeatability, and noise level shall be made on the most sensitive instrument range to insure that it conforms with the instrument performance specifications.

A5.3.3 Daily Routine

(1) If analyser power is not left on continuously, allow two hours for warmup.

(2) Clean or replace filters.

(3) Check system for leaks.

(4) Ascertain that flow to detector is correct.

(5) Check zero with zero-grade nitrogen.

(6) Zero and span shall be checked before and after each test and also at approximately one-hour intervals during the test.

A6. REFERENCE GASES

A6.1 Mixture Composition: Reference gases for carbon monoxide and carbon dioxide shall be prepared using nitrogen as the diluent. They may be blended singly or as dual component mixtures. Nitric oxide reference gas shall be blended in nitrogen. Hydrocarbon reference gas shall be propane in air. Zero gas shall be nitrogen, or optionally high purity air as specified in A6.4.

A6.2 Calibration Gases: Calibration gases shall be certified by the vendor as accurate within ± 1%.

A6.3 Span Gases: Span gases shall be supplied by the vendor to a stated accuracy within ± 2%.

A6.4 Zero Gas: Nitrogen zero gas shall be minimum 99.998% $N_2$ with less than 1 ppm CO. This gas shall be used to zero the CO, $CO_2$ and NO analyser.

Zero-grade air shall not exceed 0.1 ppm hydrocarbon. This gas shall be used to zero the HC analyser. Zero-grade air includes artificial air consisting of a blend of $N_2$ and $O_2$ with $O_2$ concentration between 18 and 21 mole percent.

A7. TEST PROCEDURE

A7.1 Test Layout: Set up engine, sampling equipment, and analysis equipment as specified in Sections A3 and A4.

A7.2 Fuel: The fuel used shall be as specified by the engine manufacturer. The carbon-to-hydrogen ratio shall be determined; this parameter is required in the calculation of results (Section A9). The emissions levels determined by this procedure may be a function of the type of fuel used, and, therefore, the type of fuel shall be included as an integral part of the test data, as specified in Section A8.

A7.3 Ambient Conditions

A7.3.1 Ambient Temperature, Pressure, and Humidity. Changes in ambient temperature, pressure, and humidity can cause changes in emissions levels both through direct changes in combustor conditions and through changes in engine operating parameters. Since generally accepted methods are not currently available for correcting test data to standard conditions, extremes of ambient conditions should be avoided. Ambient temperature, pressure, and humidity shall be measured for the test record (Section A8), but these data are not required for calculation purposes.

A7.3.2 Wind Velocity and Direction. The wind velocity and direction shall be recorded, and the crosswind and tailwind components shall be calculated. The crosswind velocity component shall not exceed 5 mph during the test. The tailwind component shall not exceed 1 mph.

A7.3.3 Ambient Air Composition. Unusually high concentrations of CO, HC, and $CO_2$ in the ambient air should be avoided since high values can adversely affect data accuracy. For comparison purposes, standard air contains 300 ppm $CO_2$, and the EPA ambient air quality standards are 9 ppm, 0.24 ppm, and 0.05 ppm for CO, HC, and $NO_2$ respectively. Unusually high concentrations may indicate abnormal conditions such as exhaust gas ingestion, fuel spillage, or additional sources of these emissions in the test area. It is suggested that an ambient air sample be obtained with the engine running before obtaining emissions data at each power setting.

A7.4 Instrument Calibration. Calibrate exhaust analysis instruments before and after each test period using daily procedures given in Section A5.

A7.5 Test Sequence

(a) Start engine and adjust to desired power setting, allow adequate time for stabilisation.

(b) Measure concentrations of CO, $CO_2$, HC, NO, and $NO_x$ at 11 radial sampling locations as specified in Section A3.2.2.

(c) The engine may then be stabilised at another power setting and measurements made as in (b) above. Repeat until test series is complete.

A8 MINIMUM INFORMATION TO BE RECORDED.

The following information, as applicable, shall form a part of the permanent record for each test.

A8.1 General:

(a) Facility performing test and location.

(b) Individual responsible for conduct of test.

(c) Test number, reading number, etc.

(d) Date.

(e) Time.

(f) Fuel type, fuel specification, additives, H/C ratio and method of determination.

(g) Ambient Conditions: temperature, pressure, humidity, wind velocity, and direction.

(h) Engine mounting position and height.

(i) Test procedure designation.

(j) Exceptions, if any, to this procedure.

A8.2 Engine Description

(a) Manufacturer

(b) Model number, serial number

(c) Time since overhaul and other pertinent maintenance information.

(d) Nozzle exit diameter (per Section A3.2) and method of determination.

A6.3 Engine Operating Data:

(a) Nominal power setting, throttle angle.

(b) Rotational speed: $N_1$, $N_2$.

(c) Fuel flow (main engine and afterburner).

(d) Airflow and method of determination.

(e) Compressor discharge temperature and method of determination.

(f) Compressor discharge pressure or EPR.

(g) Exhaust nozzle position.

(h) Thrust.

A6.4 Exhaust Sampling Data:

(a) Axial sampling location.

(b) Radial sampling location (distance from projected engine centerline).

(c) Concentrations of CO, $CO_2$, HC, HU, and $NO_x$ at each sampling location.

(d) Sample line temperature.

(e) Probe coolant temperature.

A9 CALCULATION OF RESULTS

A9.1 General Calculations Procedure. Calculation of results involves the following steps:

(a) Correction of measured concentrations to actual or wet concentrations of CO, $CO_2$, HC, NO, and $NO_x$.

(b) Calculation of the slope of a linear fit, by the method of least squares, of the concentration of each pollutant plotted against the concentration of $CO_2$.

(c) Calculation of emission indices (lb per 1000 lb of fuel) for CO, HC, NO, and $NO_x$ from the slopes found in (b) above.

(d) Calculation of emission flow rate (lb per hr) from emission indices found in (c) above and the total engine fuel flow rate.

A9.2 Symbols

(CO) = Actual (wet) concentration of CO in exhaust, ppm.

($CO_2$) = Actual (wet) concentration of $CO_2$ in exhaust, %.

(HC) = Actual (wet) concentration of hydrocarbon in exhaust, expressed as ppm equivalent methane.

(NO) = Actual (wet) concentration of NO in exhaust, ppm.

($NO_x$) = Actual (wet) concentration of $NO_x$ in exhaust, ppm.

$(CO)_d$, $(CO_2)_d$, etc. = Dry concentration of CO, $CO_2$, etc.

$(CO)_{sd}$, $(CO_2)_{sd}$, etc. = Sand-dry (0.60% moisture) concentrations of CO, $CO_2$, etc.

a, b = Constants in linear curve fit relationship.

y, x = Variables in linear curve fit relationship; y represents pollutant concentrations (wet) in ppm; x represents $CO_2$ concentration (wet) in %.

$Y_i$, $X_i$ = Actual (wet) concentration of pollutant ($Y_i$) and $CO_2$ ($X_i$) at each sampling point.

n = Total number of sampling points (i = 1 to n).

r = Correlation coefficient.

WFE = Total engine (mainburner plus afterburner) fuel flow rate, lb per hr.

$E'_E$ = Emission index of pollutant E, lb per 1000 lb fuel

$W_E$ = Emission flow rate of pollutant E, lb per hour

n = hydrogen to carbon atomic ratio of fuel

$K_d$ = Correction factor for water of combustion

$K_w$ = Correction factor for water of combustion and water vapor in the inlet air

h = Water content (humidity) of inlet air (% by volume)

$M_C$ = Atomic weight of carbon

$M_H$ = Atomic weight of hydrogen

$\sigma_y$ = Standard deviation of y variable

$\sigma_a$ = Standard deviation of a

$\sigma_b$ = Standard deviation of b

A9.1 Correction for Moisture. All measured concentrations shall be corrected for moisture, as required, in order to form a consistent basis for further calculations. The calculation procedure presented here is for conversion to actual or wet concentration, although any reference moisture level may be used as long as it is consistent for all species in an equation.

The correction factor $K_d$ corrects measured concentrations for water of combustion. The factor $K_w$ corrects measured concentrations for water of combustion and for moisture in the inlet air. The values of $K_d$ and $K_w$ depend on the moisture removal devices in the analysis system. Note that no moisture removal device is permitted in the $NO_x$ or HC analyser sample lines so that HC and $NO_x$ are always measured on a wet basis. If an ice trap (32° F) is used to partially dry the CO and $CO_2$ analyser samples, then the CO and $CO_2$ samples are semidry and contain 0.602% moisture. Factors for converting CO and $CO_2$ concentrations to appropriate wet values are:

$$K_d = \frac{100}{100 + 1.006\,n\left(\frac{(CO)_{sd}}{10^4} + (CO_2)_{sd}\right)} \qquad (81)$$

$$K_w = \frac{200 - h\,(1 + n/2)}{200 - h + \frac{n}{2}\,h\left(1 - \frac{1.006\,(CO)_{ad}}{10^6}\right)} \qquad (B2)$$

where $(CO)_{ad}$ and $(CO_2)_{ad}$ are the measured semi-dry concentrations. Then,
Concentration (wet) = $K_w$ x 1.006 x Concentration (semi-dry).

## A9.4 Calculation of the Slope of Emissions vs. $CO_2$ by the Method of Least Squares

At a given engine power setting, the linearity of CO, HC, NO, and $NO_x$ with respect to $CO_2$ shall be determined, by analysis of the measurements collected at the various probe sampling locations, in the following manner.

(a) Using the method of least squares, a polynominal of the form:

$$y = a + b\,x \qquad (B3)$$

shall be fitted to each pollutant (CO, HC, NO, $NO_x$), in turn, where y represents the wet concentration (ppm) of the pollutant being analysed, and x is the wet concentration (%) of $CO_2$. The constants a and b are determined by the well-known least square relationships (Reference 45):

$$a = \frac{\Sigma X_i \Sigma X_i Y_i - \Sigma Y_i \Sigma X_i^2}{(\Sigma X_i)^2 - m\Sigma X_i^2} \qquad (B4)$$

$$b = \frac{\Sigma X_i \Sigma Y_i - m\Sigma X_i Y_i}{(\Sigma X_i)^2 - m\Sigma X_i^2} \qquad (B5)$$

$X_i$ and $Y_i$ represent the concentrations of X and Y at the ith sampling location of the particular test point, and the summations are over the total number (m) of sampling locations at which gas samples were extracted.

The slope, b, of the linear fit is proportional to the emission index. The intercepts are related to the ambient concentrations. Note that the Y intercept, a, should be no greater than the ambient pollutant level, and the x intercept, - a/b, should be no greater than the ambient $CO_2$ level. Ambient level is taken to be concentrations in the local air with which the engine exhaust mixes.

(b) The appropriateness of the linear fit of each constituent versus $CO_2$ shall be determined by calculation of the correlation coefficient (r) for each constituent, defined by the equation (Reference 45):

$$r = \frac{m\Sigma X_i Y_i - \Sigma X_i \Sigma Y_i}{\sqrt{[m\Sigma X_i^2 - (\Sigma X_i)^2][m\Sigma Y_i^2 - (\Sigma Y_i)^2]}} \qquad (B6)$$

Values of r near 1.00 indicate good data consistency over the plume diameter, that plume reactions have ceased, and that plume mixing is complete. If the slope, b, is greater than about 10, then r should be greater than 0.99 if measurements are carefully made. For smaller values of b, r is influenced by instrument sensitivity, and low values may result.

Low values of r may be an indication that plume reactions are not complete. If b is greater than 10 and r is less than 0.95, the measurements shall be repeated at a sampling station further downstream from the engine. The new sampling station shall be at a distance from the engine exhaust plume 1.3 to 1.4 times the distance of the previous measurements.

(c) The following standard deviations shall be computed and reported for each pollutant as a statistical measure of the degree of error associated with each term in the curve fit (Reference 46):

$$\sigma_y = \sqrt{\frac{\Sigma (Y_i - a - bX_i)^2}{m-1}} \qquad (B7)$$

$$\sigma_a = \sigma_y \sqrt{\frac{m\Sigma X_i^2}{(m-1)[m\Sigma X_i^2 - (\Sigma X_i)^2]}} \qquad (B8)$$

$$\sigma_b = \sigma_y \sqrt{\frac{m}{(m-1)[m\Sigma X_i^2 - (\Sigma X_i)^2]}} \qquad (B9)$$

## A9.5 Calculation of the Emission Indices of CO, HC, NO, $NO_x$

The emissions indices (lb/1000 lb fuel) of CO, HC, NO and $NO_x$ at a given test condition shall be determined from the values of b (Section A9.4a, Equation B3) obtained for each pollutant using the following equations:

$$EI_{CO} = (W_f + nW_a) \frac{1.001}{\left(1 + \frac{b_{CO} + b_{HC}}{10^4}\right)} \left(\frac{b_{CO}}{\quad}\right) \qquad (B10)$$

$$BI_{HC} = \frac{0.106\ (b_{HC})}{1 + \frac{b_{CO} + b_{HC}}{10^4}} \tag{B11}$$

$$BI_{NO} = \frac{0.601\ (b_{NO})}{(N_0 + nN_0)\left(1 + \frac{b_{CO} + b_{HC}}{10^4}\right)} \tag{B12}$$

$$BI_{NO_2} = \frac{0.601\ (b_{NO_2})}{(N_0 + nN_0)\left(1 + \frac{b_{CO} + b_{HC}}{10^4}\right)} \tag{B13}$$

A9.6 Calculation of Emissions Flow Rates for CO, HC, NO, $NO_x$

The emissions flow rates (lb/hr) of CO, HC, NO, $NO_x$ shall be determined from the equation:

$$M_s = .001\ (BI_s)\ (WFE) \tag{B14}$$

where s represents CO, HC, NO, and $NO_x$.

## PART B. REAR PLANE METHOD (MEASUREMENT PROCEDURE FOR SAMPLING AT NOZZLE EXIT PLANE)

### B1. DEFINITIONS

B1.1 Aircraft Gas Turbine Engine: A turboprop, turbofan, or turbojet aircraft engine.

B1.2 Engine Exhaust: Flow of material from an engine as a result of the combustion of fuel and oxidizer.

B1.3 Exhaust Emissions: Substances ejected into the atmosphere from the exhaust discharge nozzle of an aircraft engine.

B1.4 Particulates: Solid exhaust emissions.

B1.5 Smoke: Matter in exhaust emissions which obscures light transmission.

B1.6 Augmentor: A device or method used to obtain thrust in addition to that provided by normal operation of the main engine.

B1.7 Afterburning Gas Turbine Engine: A gas turbine engine in which thrust augmentation is provided by injection and combustion of additional fuel in an afterburner. The afterburner is located between the turbine and the exhaust nozzle. The term "afterburner" generally applies to a turbojet engine. If the engine is a turbofan type, thrust augmentation may be obtained by burning in the fan stream (fanburner or ductburner) or in the combined core stream and fan stream (mixed-flow augmentor).

B1.8 Pollutant: Objectionable exhaust emission.

B1.9 Plume: Total external engine exhaust including ambient air with which the exhaust mixes.

B1.10 Total Hydrocarbons (abbreviated HC): The total of hydrocarbons of all classes and molecular weights in the engine exhaust.

B1.11 Oxides of Nitrogen (abbreviated $NO_x$): The total of oxides of nitrogen in the engine exhaust. The total $NO_x$ value is calculated as equivalent $NO_2$.

B1.12 Flame Ionization Detector: A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass flow rate of hydrocarbons entering the flame per unit of time, generally assumed responsive to the number of carbon atoms entering the flame.

B1.13 Nondispersive Infrared Analyser: An instrument that selectively measures specific components by absorption of infrared energy.

B1.14 Chemiluminescence Analyser: An instrument in which the intensity of light produced by the chemiluminescence of the reaction of nitric oxide with ozone is proportional to the concentration of nitric oxide. Conversion of $NO_2$ to NO prior to entering the analyser permits the determination of both species.

B1.15 Interference: Instrument response due to components other than the gas that is to be measured.

B1.16 Calibrating Gas: Gas of known concentration used to establish instrument response.

B1.17 Span Gas: A calibrating gas used routinely to check instrument response.

B1.18 Zero Gas: A calibrating gas used routinely to check instrument zero.

B1.19 Concentration: The volume fraction of the component of interest in the gas mixture, expressed as volume percentage or as parts per million.

B2. ANALYSIS EQUIPMENT

B2.1 NDIR Instruments: Nondispersive infrared (NDIR) analysers shall be used for the continuous monitoring of carbon monoxide (CO) and carbon dioxide ($CO_2$) in the turbine exhaust.

The NDIR instruments operate on the principle of differential energy absorption from parallel beams of infrared energy. The energy is transmitted to a differential detector through parallel cells, one containing a reference gas, and the other, sample gas. The detector, charged with the component to be measured, transduces the optical signal to an electric signal. The electrical signal thus generated is amplified and continuously recorded.

B2.1.1 Instrument Performance Specifications:

Response Time (electrical) - 90% full scale response in 0.5 second or less.
Zero Drift - Less than ± 1% of full scale in 2 hours on most sensitive range.
Span Drift - Less than ± 1% of full scale in 2 hours on most sensitive range.
Repeatability - Within ± 1.0% of full scale.

Noise - Less than ± 1.0% of full scale on most sensitive range.
Sample Cell Temperature - Minimum 50° C (122° F) maintained within ± 3° C (1.6° F).

B2.1.4 Range and Accuracy

| | Range | Accuracy Excluding Interferences |
|---|---|---|
| Carbon Monoxide | 0 to 100 ppm | ± 2% of full scale |
| | 0 to 500 ppm | ± 1% of full scale |
| | 0 to 2,500 ppm | ± 1% of full scale |
| | 0 to 20,000 ppm | ± 1% of full scale |
| Carbon Dioxide | 0 to 2% | ± 1% of full scale |
| | 0 to 5% | ± 1% of full scale |
| | 0 to 15% | ± 1% of full scale |

B2.1.3 NDIR Cells: All NDIR instruments shall be equipped with cells of suitable length to measure concentrations within the above ranges to the indicated accuracy. Range changes may be accomplished by use of stacked sample cells and/or changes in the electronic circuitry.

B2.1.4 Interferences: Interferences from water vapor, carbon dioxide, and carbon monoxide shall be determined on the most sensitive instrument range. Response of CO instruments shall be less than 5% of full scale for 2.5% $CO_2$, or 4% water vapor. Optical filters are the preferred method of discrimination. In some cases a cold trap or drying agent may be necessary to reduce water content below the level at which its interference is acceptable.

B2.2 Total Hydrocarbon Analyzer: The measurement of total hydrocarbon is made by an analyzer using a flame ionization detector (FID). With this type detector an ionization current, proportional to the mass rate of hydrocarbon entering a hydrogen flame is established between two electrodes. This ionization current is measured using an electrometer amplifier and is continuously recorded.

B2.2.1 General Design Specifications: The analyzer shall be fitted with a constant temperature oven housing the detector and sample-handling components. It shall maintain temperature within ± 2° C of the set point, which shall be within the range 155 to 165° C (311-329° F).

The detector and sample handling components shall be suitable for continuous operation at temperatures to 200° C (392° F).

82.2.2 Instrument Performance Specifications:

Response Time (electrical) - 90% of full scale in 0.5 second or less.
Noise - Less than ± 1.0% of full scale on most sensitive range.
Repeatability - Within ± 1.0% of full scale.
Zero Drift - Less than ± 1% of full scale in 4 hours on all ranges.
Span Drift - Less than ± 1% of full scale in 2 hours.
Linearity - Response with propane in air shall be linear within ± 1% over the range of 0 to 3,000 ppmC.

82.2.3 Range and Accuracy

| Range | Accuracy |
|---|---|
| 0 to 10 ppmC: | ± 5% of full scale with propane calibration gas. |
| 0 to 100 ppmC: | ± 2% of full scale with propane calibration gas. |
| 0 to 1,000 ppmC: | ± 1% of full scale with propane calibration gas. |
| 0 to 10,000 ppmC: | ± 1% of full scale with propane calibration gas. |

82.3 Chemiluminescence Analyzer

82.3.1 General Instrument Description: A chemiluminescence analyzer with thermal converter shall be used for measuring nitric oxide (NO) and total oxides of nitrogen ($NO_x$). The chemiluminescence method utilizes the principle that NO reacts with ozone ($O_3$) to give nitrogen dioxide ($NO_2$) and oxygen ($O_2$). Approximately 10 percent of the $NO_2$ is electronically excited. The transition of excited $NO_2$ to the ground state yields a light emission (600-3400 nanometer region) at low pressures. The detectable region of this emission depends on the PM-tube/optical filter being used in the detector. The intensity of this emission is proportional to the mass flow rate of NO into the reactor. The light emission can be measured utilizing a photomultiplier tube and associated electronics.

The method also utilizes the principle that $NO_2$ thermally decomposes to NO ($2NO_2 + 2NO + O_2$). A thermal converter unit designed to provide essentially complete conversion of $NO_2$ to NO is included as a part of the chemiluminescence analyzer package. If the sample is passed through the converter prior to entering the chemiluminescence analyzer, an $NO_x$ reading (NO + $NO_2$) is obtained. If the converter is bypassed, only the NO portion is indicated.

82.3.2 Instrument Performance Specifications

Response time (electrical) = 90% of full scale in 0.5 second or less.
Noise = Less than 1% of full scale.
Repeatability = ± 1% of full scale.
Zero drift = Less than ± 1% of full scale in 2 hours.
Span drift = Less than ± 2% of full scale in 2 hours.
Linearity = Linear to within ± 2% of full scale on all ranges.
Accuracy = ± 1% of full scale on all ranges.

83. SAMPLING EQUIPMENT

83.1 Sampling Probe:

83.1.1 Design Concept: Local exhaust gas temperature at the nozzle exit plane of afterburning engines may be as high as 3500° F with corresponding total pressures 30 to 40 psia. Extremely careful design of the probe coolant passages is required to remove the heat resulting from impingement of the hot gases on the probe surface. The coolant must have good heat transfer properties (water is preferred), and high coolant velocities must be maintained, especially at the probe leading edge.

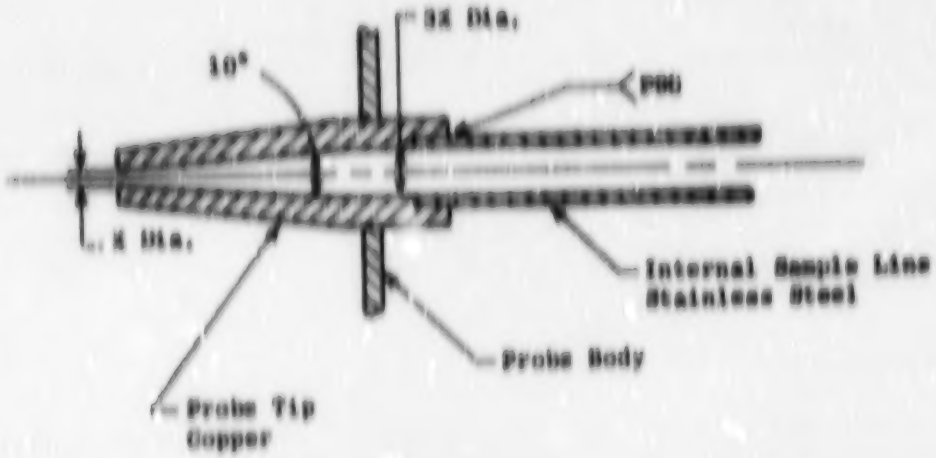
In order to prevent continued chemical reaction within the probe, a quenching-type probe is required. Quenching of the reactions is accomplished by adequate cooling of the tip and by expansion of the gas flow across the orifice.

In order to properly mass weight the various samples, impact pressure must be measured at the sampling point. Local mass flow is subsequently calculated from the local impact pressure, static (ambient) pressure, and total temperature (calculated from the gas composition). The mass weighting implies that individual samples must be taken. Due to potential nonhomogeneities in the exhaust stream, both radially and circumferentially, a relatively large number of samples are required. Either a movable probe (single element) or a fixed rake (multiple element) may be used. In either case, accurate positioning of the probe is required.

83.1.2 Probe Material: The parts of the probe wetted by the sample gas, except for the probe tip, should be of stainless steel. Other material may be used in contact with the sample gas, if it is demonstrated that the material does not alter the composition of the sample. To assure adequate cooling, the probe tip shall be of copper (AMS 4500).

83.1.3 Probe Temperature: The sample line within the probe shall be maintained at a temperature between 130 and 337° F.

B3.1.4 Probe Tip Design: The probe tip orifice shall be sized so as to give adequate sample flow under critical flow conditions. A short expansion section directly following shall enlarge the flow passage to a minimum diameter of three times the orifice diameter. A typical probe tip design is shown below:




B3.1.5 Total Pressure Measurement: Total pressure shall be measured within 0.2 inch of the sampling location. This permits a combination probe tip design in which separate orifices are provided for the gas sample and impact pressure measurements. Alternatively, both pressure measurement and gas sample may be obtained from a single orifice, in which case the measurements cannot be made simultaneously.

B3.2 Sampling Locations:

B3.2.1 Axial Sampling Plane: The axial sampling plane shall be within eight inches of the plane at which the exhaust is completely expanded. Care should be taken so that adequate clearance exists between the sampling probe and exhaust nozzle for every position of the exhaust nozzle during the test.

B3.2.2 Radial Sampling Locations: A minimum of 20 sampling points shall be used for each test condition. A minimum of five sampling points shall be located in each of four quadrants, with two sampling points located

near the engine centerline. Sampling points in adjacent quadrants shall be separated by at least 60 degrees angular displacement.

Adjacent sampling points along each diameter should be equally spaced. In order to accurately locate the edge of the exhaust stream, the impact pressure at the outermost sampling point shall be between 1.05 $P_{amb}$ and 1.10 $P_{amb}$, where $P_{amb}$ is the ambient pressure.

B3.3 Sample Transfer: The sample shall be transferred from the probe to the analytical instruments through a heated sample line of either stainless steel or teflon of 0.18 to 0.32-inch ID. The sample lines shall be maintained at a temperature of 300 ± 27° F from the probe to each analytical instrument.

Sample line length should be as short as possible, consistent with the test setup. Suitable noncontaminating sample pumps shall be used to maintain a partial vacuum within the probe so that the pressure ratio across the probe orifice is no less than five. The total sample flow rate shall be such that the sample gas is transported from the probe inlet to the analyser inlet in less than ten seconds.

B4. EQUIPMENT LAYOUT

A schematic diagram of the emissions measuring system is shown in Figure B2. Additional components such as instruments, thermocouples, valves, solenoids, pumps, and switches may be used to provide additional information and coordinate the functions of the component systems. Parallel installation of CO and $CO_2$ analysers is an acceptable alternative. No desiccants, dryers, water traps or related equipment may be used to treat the sample flowing to the $NO_x$ analyser. The $NO_x$ instrument configuration must be such that water condensation is avoided throughout the instrument.

B5. INSTRUMENT ROUTINES

B5.1 HDIR Instruments: Following the instrument manufacturer's instructions for startup of instruments, the following minimum requirements shall be adhered to:

B5.1.1 Monthly Routine:

(1) Check detector tuning, following manufacturer's prescribed routine.

(2) Set instrument zero using dry nitrogen.

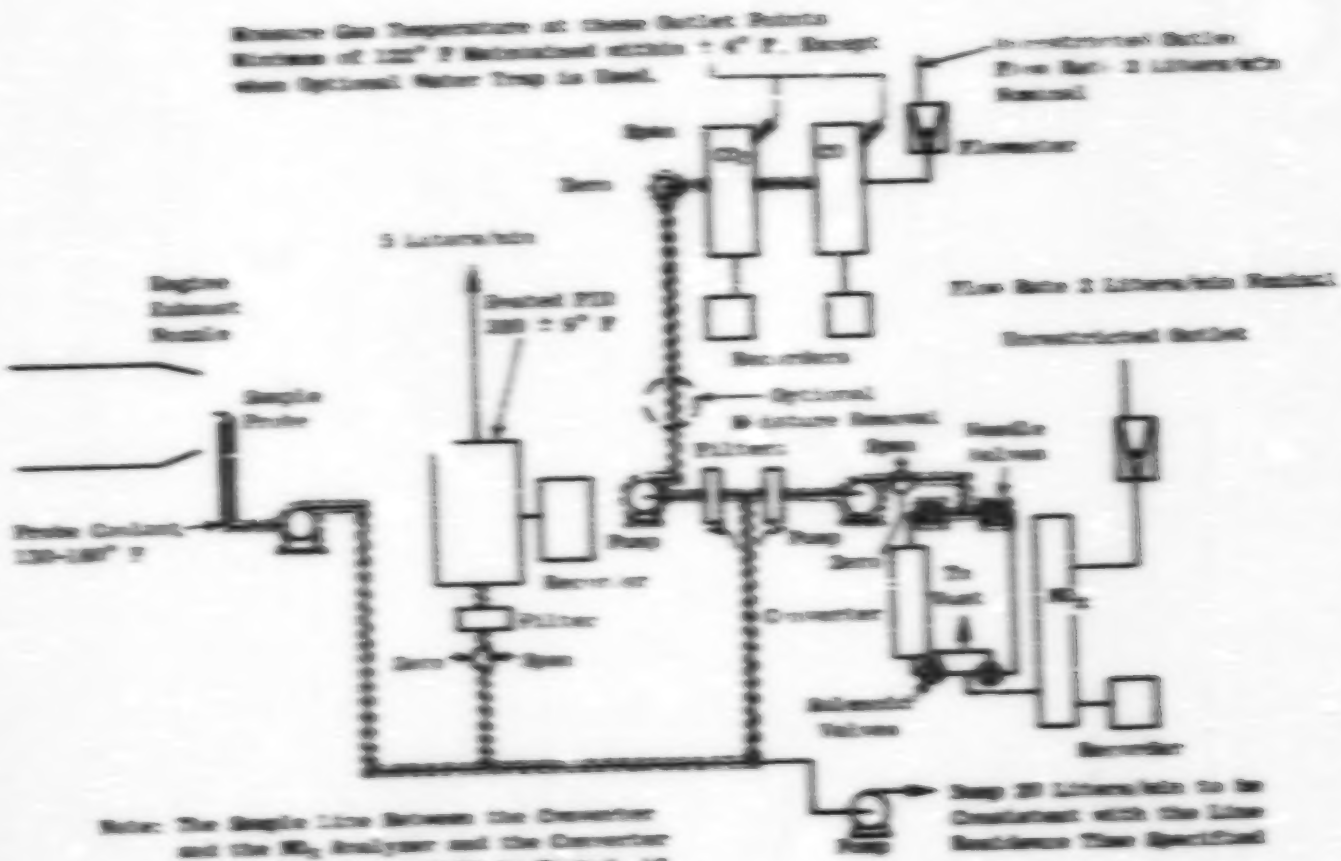


Figure B2. Sampling System Schematic. Instrument Layout is the Same as in Figure B1, Major Difference is the Probe Pump.

(3) Using previous gain setting check calibration curves using calibration gas with nominal concentrations of 30, 60, and 90% of each range used. Use the same gas flow rate through instruments during calibration as when sampling exhaust. Any response value differing from the previous value by more than ± 3% of the previous value at the same gain setting may reflect some problem in the instrument system, and a thorough instrument check should be made. Confirm or reestablish calibration curves for each range. Log gain reading.

(4) Check response of interference gases as called out in 85.1.4. If unacceptable, determine cause and correct -- detector replacement may be indicated.

85.1.2 Daily Routine:

(1) If analyzer power is not left on continuously, allow 2 hours for warmup. (If daily use is anticipated, it is recommended that analyzer be left on continuously.)

(2) Replace or clean filters.

(3) Check system for leaks.

(4) Check detector tuning and record reading. If the reading changes by more than ± 3% from the previous value, instrument readjustment is indicated. For the following tests the temperature of zero and span gas in the instrument cells shall be within ± 3° C (± 5.6° F) of typical sample gas temperature measured at the outlet of the sample cell, and gas flow rate through the instruments shall be the same for zero and span gas as for sample gas.

(5) Zero the instrument on dry nitrogen. If there is a significant change in setting of zero control, determine the cause and correct.

(6) Using span gas to give 75 to 90% full-scale deflection, check the response of the instrument on each range using the gain setting from the previous use. If the reading differs from the previous value by more than 3%, an instrument problem may be indicated. Check and correct as necessary. If instrument reading is within ± 3% of previous value, adjust gain control to produce proper instrument output. Log gain setting at final adjustment.

(7) Check zero with dry nitrogen and repeat step 6 if necessary.

(8) Zero and span shall be checked before and after each test, and at approximately one-hour intervals during the test.

## 85.2 Total Hydrocarbon Analyzer

### 85.2.1 Initial Alignment:

#### 85.2.1.1 Optimization of Detector Response:

(1) Follow manufacturer's instructions for instrument startup and basic operating adjustment. Fuel shall be 60% helium, 40% hydrogen containing less than 0.1 ppmC hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 0.1 ppmC.

(2) Set oven temperature at 160° C ± 5° C (320° F ± 9° F) and allow at least one-half hour after oven reaches temperature for the system to equilibrate. The temperature is to be maintained at set point ± 2° C (± 3.6° F).

(3) Introduce a mixture of propane in air at a propane concentration of about 500 ppmC. Vary the fuel flow to burner and determine the peak response. A change in zero may result from a change in fuel flow; therefore, the instrument zero should be checked at each fuel flow rate. Select an operating flow rate that will give near maximum response and the least variation in response with minor fuel flow variations.

(4) To determine the optimum airflow, use fuel flow setting determined above and vary airflow. A typical curve for response versus airflow is shown below:

After the optimum flow settings have been determined, these flows are to be measured and recorded for future reference.

85.2.1.2 Oxygen Effect: Check the response of the detector with varied concentrations of oxygen in the sample following steps outlined below; this test shall be made with oven temperature at the set point and with gas flow to the detector at optimum conditions, as determined in 85.2.1.1.

(1) Introduce nitrogen ($N_2$) zero gas and zero analyser; check zero using hydrocarbon-free air; the zero should be the same.

(2) The following blends of propane shall be used to determine the effect of oxygen ($O_2$) in the sample:

Propane in $N_2$

Propane in 90% $N_2$ + 10% $O_2$

Propane in air

The volume concentration of propane in the mixture reaching the detector should be about 500 ppmC, and the concentration of both the $O_2$ and the hydrocarbon should be known within ± 1% of the absolute value. The zero should be checked after each mixture is measured. If the zero has changed, then the test shall be repeated.

The response to propane in air shall not differ by more than 1% from the response to propane in the 10%-$O_2$/90%-$N_2$ mixture, nor differ by more than 5% from the response to propane in nitrogen.

If these specifications cannot be met by changing the sample flow rate or burner parameters, such as airflow and/or fuel flow rate, it is recommended that the detector be replaced.

85.2.1.3 Linearity and Relative Response:

(1) With analyser optimized per 85.2.1.1, the instrument linearity shall be checked for the range 0 to 1,000 and 0 to 10,000 ppmC in air at nominal concentrations of 50 and 95% full scale of each range. The deviation of a best fit curve from a least-squares best-fit straight line should not exceed 2% of the value at any point. If this specification is met, concentration values may be calculated by use of a single calibration factor. If the deviation exceeds 2% at any point, concentration values shall be read from a calibration curve prepared during this alignment procedure.

(3) A comparison of response to the different classes of compounds shall be made using (individually) propylene, toluene, and n-hexane, each at 20 to 50 ppmC concentration in nitrogen. If the response to any one differs by more than 5% from the average of the three, check instrument operating parameters. Reducing sample flow rate improves uniformity of response.

B5.2.2 Routine At Three-Month Intervals: These checks are to be made at three-month intervals or more frequently should there be any question regarding the accuracy of the hydrocarbon measurements:

(1) Check for and correct any leaks in system.

(2) Check and optimize burner flows (air, fuel, and sample) as required by criteria of B5.2.1.1.

(3) Check $O_2$ effect as outlined in B5.2.1.2.

(4) Check response of propylene, toluene, and n-hexane as outlined in B5.2.1.3.

(5) Check linearity as outlined in B5.2.1.3.

B5.2.3 Daily Routine

(1) Clean or replace filters.

(2) Check instrument for leaks.

(3) Check instrument temperatures.

(4) Ascertain that all flows to detector are correct.

(5) Check zero with zero gas.

(6) The response using blends of propane in air shall be checked on each range:

| For range | Use |
|---|---|
| 0 to 10 ppmC | 7 to 10 ppmC propane in air |
| 0 to 100 ppmC | 70 to 100 ppmC propane in air |
| 0 to 1,000 ppmC | 700 to 1,000 ppmC propane in air |

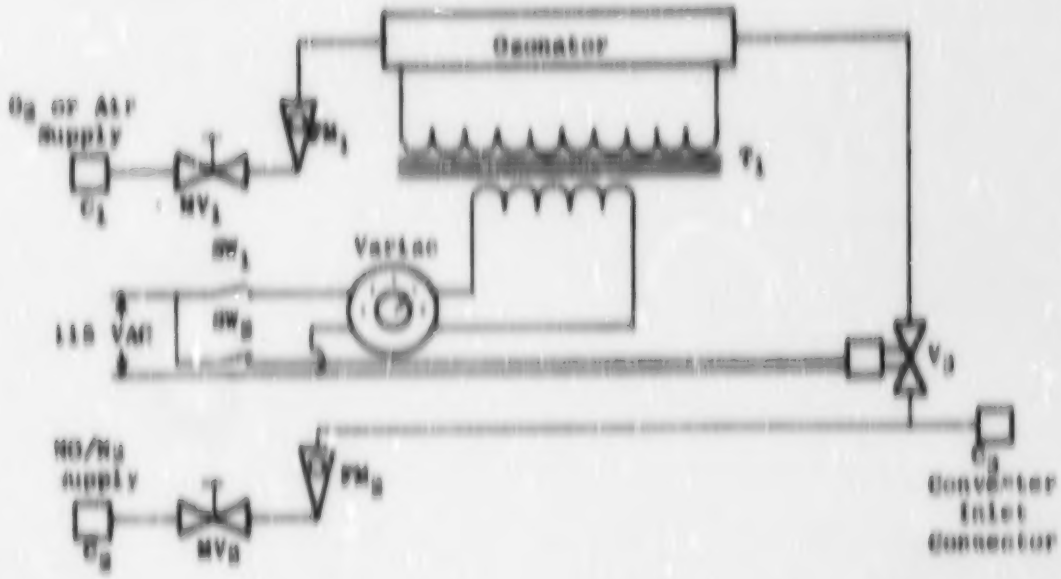
If the response differs from the last previous check value by more than 5% of the value logged during the last prior day's use, an instrument problem may be indicated.

A zero and span gas check shall be made before and after each test and at approximately one-hour intervals during the test. If the cumulative changes exceed 3% during the day, an instrument problem may be indicated.

B5.3 Chemiluminescence Analyser: Follow the instrument manufacturer's instructions for startup of instrument.

B5.3.1 Thermal Converter Efficiency Check: Check the $NO_x$ to NO converter efficiency by the following procedure. Use the apparatus described and illustrated below:

$NO_x$ Converter Efficiency Detector




(a) Attach the NO/$N_2$ supply (150-250 ppm) at $O_2$, the $O_2$ supply at $O_1$, and the analyser inlet connection to the efficiency detector at $O_3$. If lower concentrations of NO are used, air may be used in place of $O_2$ to facilitate better control of the $NO_2$ generated during step (d).

(b) With the efficiency detector variac off, place the $NO_x$ converter in bypass mode and close valve V3. Open valve MV2 until sufficient flow and stable readings are obtained at the analyser. Zero and span the analyser output to indicate the value of the NO concentration being used. Record this concentration.

(c) Open valve V1 (on/off flow control solenoid valve for $O_2$) and adjust valve MV1 ($O_2$ supply metering valve) to blend enough $O_2$ to lower the NO concentration (b) about 10%. Record this concentration.

(d) Turn on the ozonator and increase its supply voltage until the NO concentration of (c) is reduced to about 20% of (b). $NO_2$ is now being formed from the $NO+O_3$ reaction. There must always be at least 10% unreacted NO at this point. Record this concentration.

(e) When a stable reading has been obtained from (d), place the $NO_x$ converter in the convert mode. The analyser will now indicate the total $NO_x$ concentration. Record this concentration.

(f) Turn off the ozonator and allow the analyser reading to stabilise. The mixture $NO+O_2$ is still passing through the converter. This reading is the total $NO_x$ concentration of the dilute NO span gas used at step (c). Record this concentration.

(g) Close valve V1. The NO concentration should be equal to or greater than the reading of (d) indicating whether the NO contains any $NO_2$.

Calculate the efficiency of the $NO_x$ converter by substituting the concentrations obtained during the test into the following equation.

$$\text{Eff.} = \left(1 + \frac{(c) - (d)}{(f) - (c)}\right) \times 100\%$$

The efficiency of the converter should be greater than 90 percent. Adjusting the converter temperature may be needed to maximise the efficiency.

(h) If the converter efficiency is not greater than 90 percent, the cause of the inefficiency shall be determined and corrected before the instrument is used.

(i) The converter efficiency shall be checked at least monthly.

8.3.3 Monthly Routine

(1) Adjust analyser to optimise performance.

(2) Set instrument zero using zero grade nitrogen.

(3) Calibrate the $NO_x$ analyser with nitric oxide (nitrogen diluent) gases having nominal concentrations of 50 and 95% of full scale on each range used. Use the same gas flow rate through the instrument during calibration as when sampling exhaust. Log zero and gain settings.

B5.3.3 Daily Routine

(1) If analyser power is not left on continuously, allow two hours for warmup.

(2) Clean or replace filters.

(3) Check system for leaks.

(4) Ascertain that flow to detector is correct.

(5) Check zero with zero grade nitrogen.

(6) Zero and span shall be checked before and after each test and also at approximately one-hour intervals during the test.

B6. REFERENCE GASES

B6.1 Mixture Composition: Reference gases for carbon monoxide and carbon dioxide shall be prepared using nitrogen as the diluent. They may be blended singly or as dual component mixtures. Nitric oxide reference gas shall be blended in nitrogen. Hydrocarbon reference gas shall be propane in air. Zero gas shall be nitrogen, or optionally high purity air as specified in B6.4.

B6.2 Calibration Gases: Calibration gases shall be certified by the vendor as accurate within ± 1%.

B6.3 Span Gases: Span gases shall be supplied by the vendor to a stated accuracy within ± 2%.

B6.4 Zero Gas: Nitrogen zero gas shall be minimum 99.9965% $N_2$ with less than 1 ppm CO. This gas shall be used to zero the CO, $CO_2$ and NO analyser.

Zero-grade air shall not exceed 0.1 ppmC hydrocarbon. This gas shall be used to zero the HC analyser. Zero-grade air includes artificial air consisting of a blend of $N_2$ and $O_2$ with $O_2$ concentration between 18 and 21 mole percent.

## 87. TEST PROCEDURE

87.1 Test Layout: Set up engine, sampling equipment, and analysis equipment as specified in Sections 83 and 84.

87.2 Fuel: The fuel used shall be as specified by the engine manufacturer. The carbon-to-hydrogen ratio shall be determined and this parameter is required in the calculation of results (Section 89). The emissions determined by this procedure may be a function of the type of fuel used and so the type of fuel shall be included as an integral part of the test data, as specified in Section 88.

87.3 Ambient Conditions: Changes in ambient temperature, pressure, and humidity can cause changes in emissions levels both through direct changes in combustor conditions and through changes in engine operating parameters. Since generally accepted methods are not currently available for correcting test data to standard conditions, extremes of ambient conditions should be avoided. Ambient temperature, pressure, and humidity shall be measured for the test records (Section 88).

87.4 Instrument Calibration: Calibrate exhaust analysis instruments before and after each test period using daily procedures given in Section 85.

87.5 Test Sequence:

(a) Start engine and adjust to desired power setting. Allow adequate time for stabilization.

(b) Measure concentrations of CO, $CO_2$, HC, NO, $NO_x$, and impact pressure on a minimum of 32 radial sampling locations as specified in Section 83.2.3.

(c) The engine may then be stabilized at another power setting and measurements made as in (b) above. Repeat until test series is complete.

## 88. MINIMUM INFORMATION TO BE RECORDED

The following information, as applicable, shall form a part of the permanent record for each test.

88.1 General

(a) Facility performing test and location.

(b) Individual responsible for conduct of test.

(c) Test number, reading number, etc.

(d) Date

(e) Time

(f) Fuel type, fuel specification, additives, HC ratio, and method of determination.

(g) Ambient Conditions: Temperature, pressure, humidity.

(h) Test procedure designation.

(i) Exceptions, if any, to this procedure.

88.2 Engine Description

(a) Manufacturer

(b) Model number, serial number.

(c) Time since overhaul and other pertinent maintenance information.

88.3 Engine Operating Data

(a) Nominal power setting, throttle angle.

(b) Rotational speed; $N_1$, $N_2$.

(c) Fuel flow (main engine and afterburner).

(d) Airflow and method of determination.

(e) Compressor discharge temperature and method of determination.

(f) Compressor discharge pressure or EPR.

(g) Exhaust nozzle position.

(h) Thrust.

(i) Fuel temperature.

(j) Engine bypass ratio.

(k) Engine inlet (ram) total temperature.

B8.4 Exhaust Sampling Data

(a) Axial sampling location.

(b) Radial sampling location (distance from projected engine centerline).

(c) Concentrations of CO, $CO_2$, HC, NO and $NO_x$ at each sampling location.

(d) Probe impact pressure at each sampling location.

(e) Sample line temperature.

(f) Sample line pressure within probe.

(g) Probe coolant temperatures.

B9. CALCULATION OF RESULTS

For afterburning engines, chemical reactions can continue in the exhaust plumes downstream of the nozzle exit plane. The higher the exhaust temperature at the exit plane, the greater is the extent of subsequent reactions. The composition of the exhaust at the nozzle exit plane is thus not representative of the actual levels of pollutants ejected into the surrounding atmosphere, the actual levels being generally less than the levels at the nozzle exit plane. The measured emissions levels must thus be corrected for plume reactions through the use of a computer program derived from a reactive plume analytical model.

B9.1 Plume Model Input Data

The plume model computer program computes mixing and reactions along a maximum of 11 stream tubes in the plume, but the measurements are made at 33 radial probe positions. The 33 separate measurements must be reduced to 11 values before insertion into the plume model. To accomplish this, the impact pressure measurements are first plotted against radial position, as shown in Figure B3, and a smooth, averaged curve is drawn through the data. The outer radius ($R_0$) of the exhaust jet is taken as that radial location at which the impact pressure equals the ambient pressure.

Similarly, the CO and $CO_2$ concentration data are plotted against radial position (Figure B4) and smooth, average curves shall be drawn through each set of data. The plume model computer program requires that input CO and $CO_2$ composition data be on a semi-dry basis; that is, with 0.603% moisture in the sample. In case the samples were not partially dried (with an ice trap) to this level, then appropriate correction factors shall be applied. Suitable correction factors are given in Section A9.1 of this procedure.

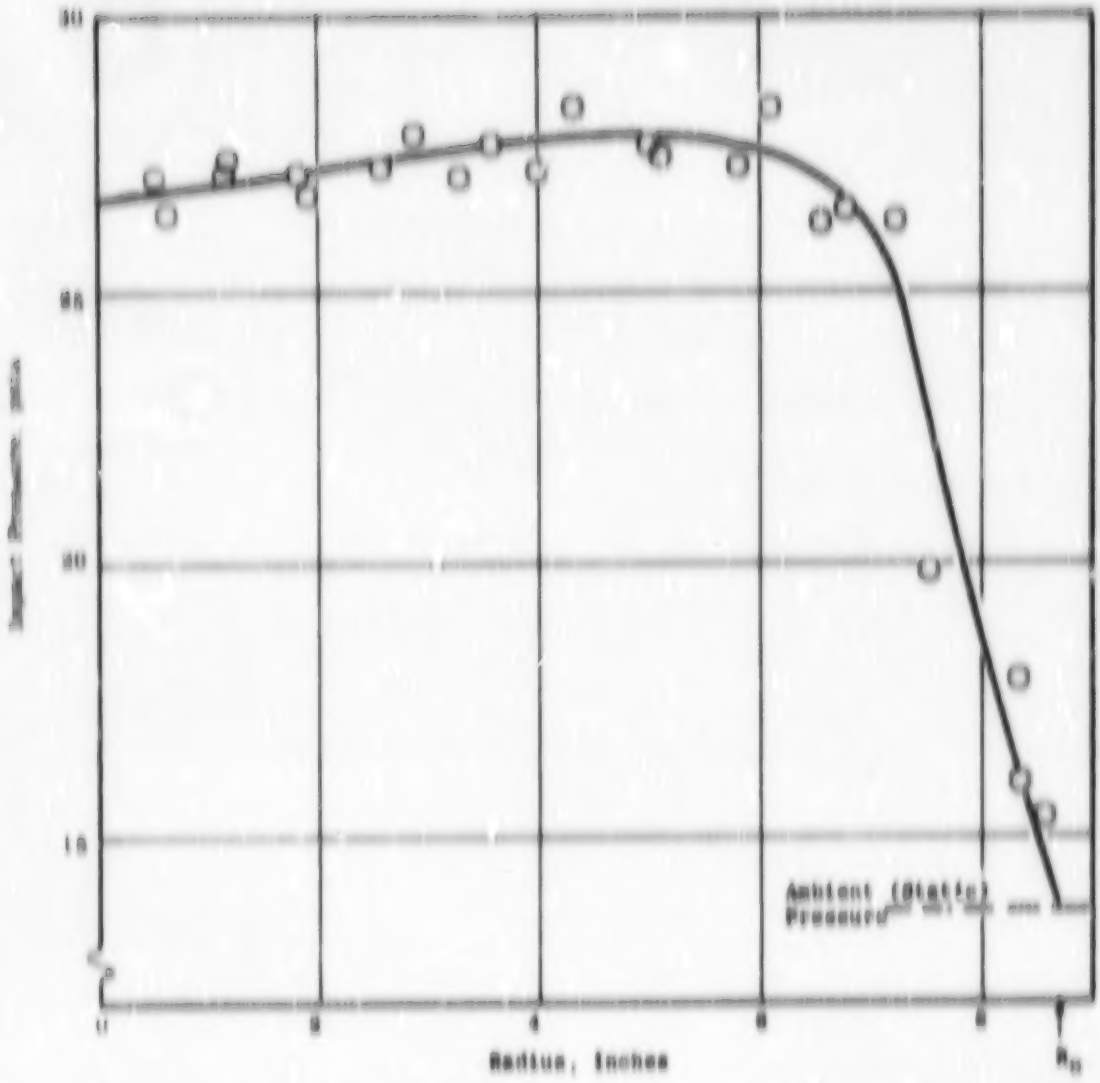



Figure 53. Impact Pressure Vs. Radial Position at Max. A/B Power Level. $R_o$ is Outer Radius of Exhaust.

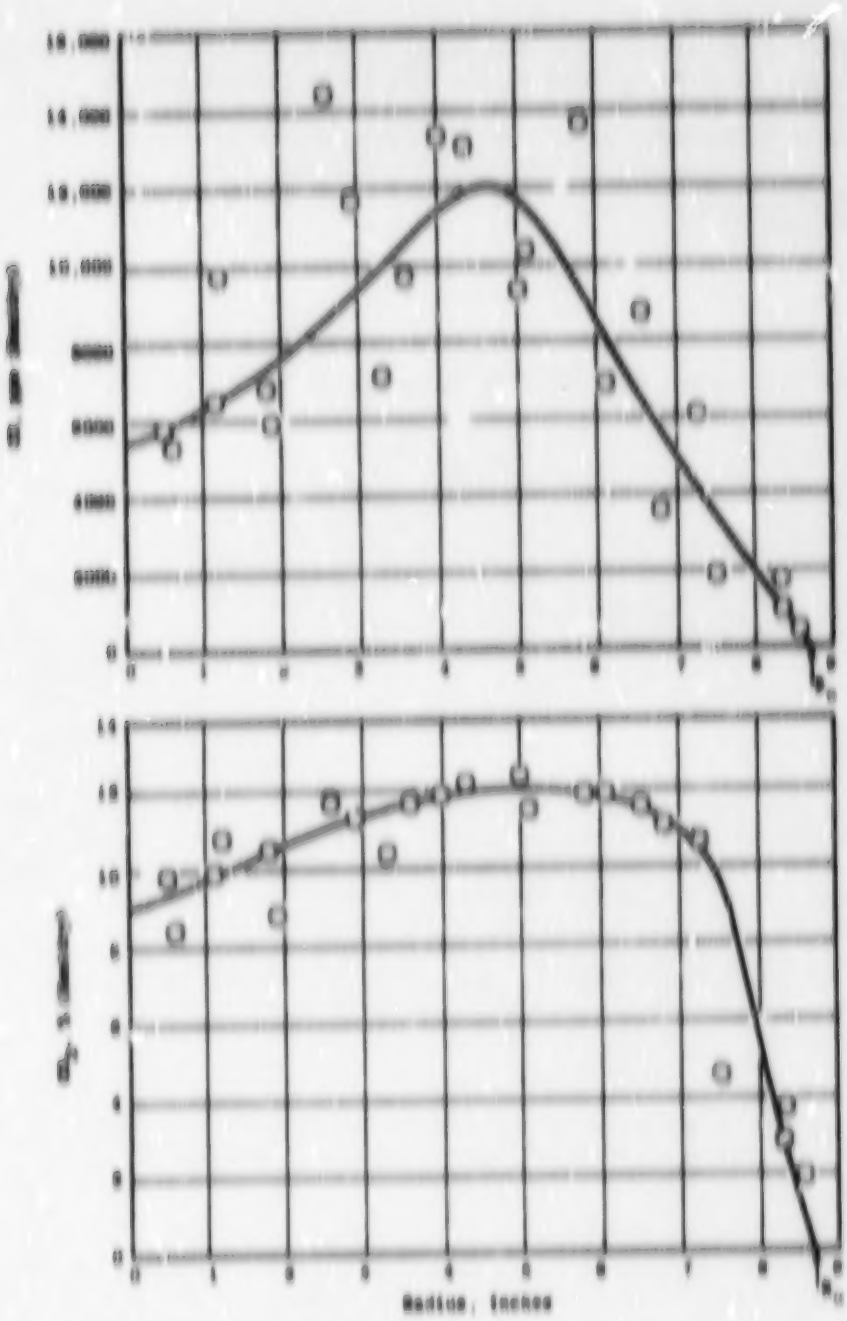



Figure 84. $(N)_R$ and (N) Concentrations Vs. Radial Position at Max. A/B Power Level. $R_o$ is Outer Radius of Exhaust.

Finally, the NO and $NO_x$ concentration data shall be plotted against radial position, as shown in Figure B5. If large variations in NO concentrations are noted across the stream, then the NO data shall be plotted on semilogarithmic coordinate paper, as in Figure B5.

The exhaust area, as determined by $R_0$, shall be divided into 11 equal areas by defining

$$a = \frac{\pi R_0^2}{11} \tag{B15}$$

The 11 radial locations, $R_i$, are then selected to be in the center of each of 11 equal areas. Thus,

$$\pi R_i^2 = \frac{(2i-1)}{2} a \tag{B16}$$

where i = 1, 2, ..., 11.

This equation can be simplified to yield

$$R_i = 0.213 \; R_0 \sqrt{(2i-1)} \tag{B17}$$

where i = 1, 2, ..., 11.

The complete list of input data required for the plume model computer program is given in Table B1 along with a brief description of each variable. Note that item 5, RADJ, is equal to $R_0$ expressed in feet. Similarly, item 13, RADII, is equal to $R_i$ expressed in feet.

The local gas composition at the 11 selected radial locations (item 12, CARDIL) must be expressed either in mole fraction, parts per million, or some unit proportional to mole fractions. Note that mixed units (e.g., ppm and %) cannot be entered. Item 19, SF, is the scale factor appropriate to the units used.

The emissions indices for $NO_x$ (EINOXC) and for CO (EICOC) at the afterburner inlet are also required for inputs to the plume model. These values are normally obtained from previous measurements on the engine at military power.

For mixed flow augmentors, in which afterburning fuel is injected into the mixed stream consisting of core engine exhaust and fan air, the overall engine bypass ratio (BETA) may be obtained from engine cycle data. The local bypass ratio (BLOC) at each probe location is generally obtained from emissions measurements at military power condition.

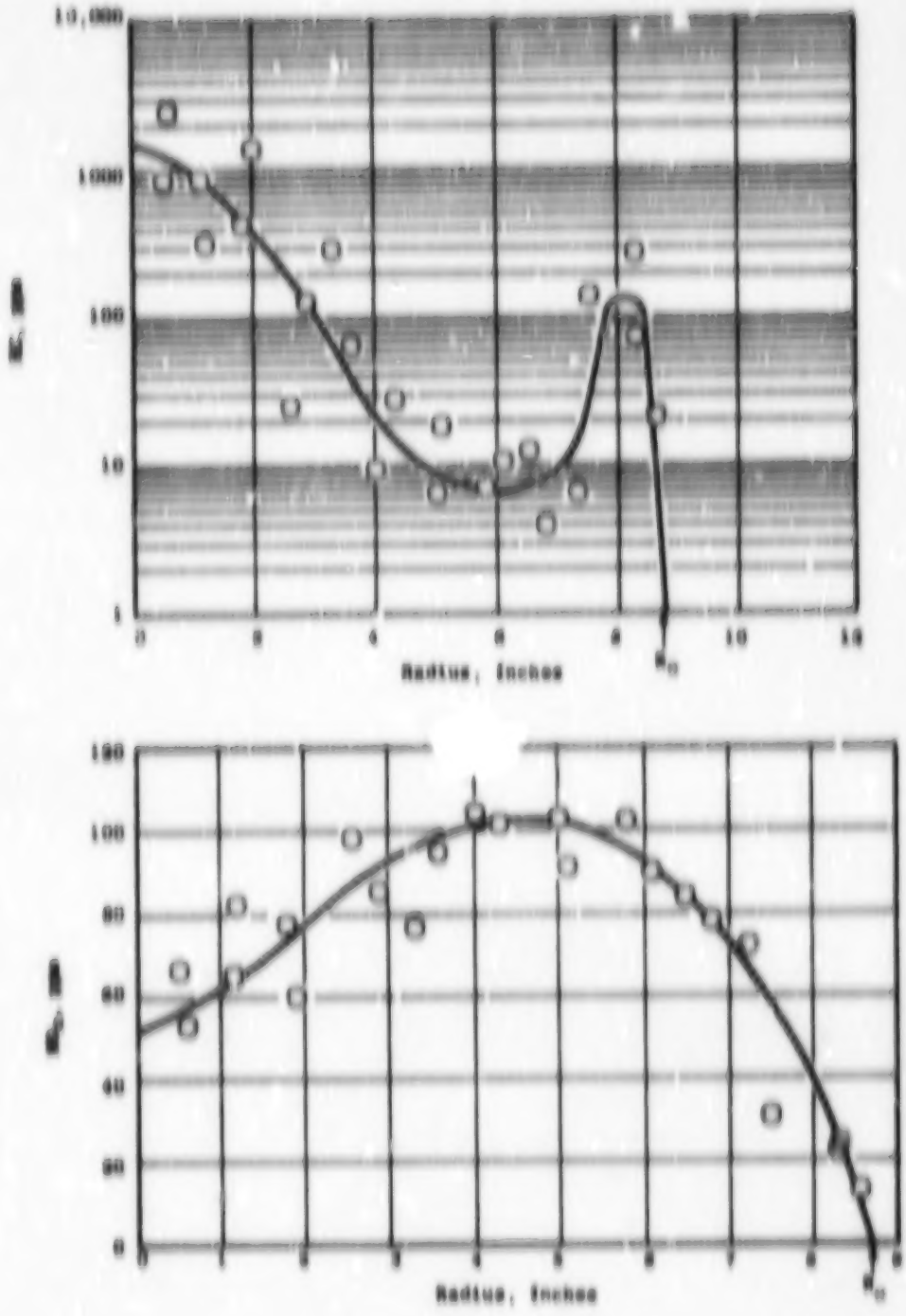



Figure 55. HI and $HO_2$ Concentrations Vs. Radial Position at Max. A/B Power Level. $R_o$ is Outer Radius of Exhaust.

Table B1. Input Data to Flame Model Computer Program.

| Item Number | Variable Name | Dimension | Default Value | Description |
|---|---|---|---|---|
| 1 | [illegible] | 1 | [illegible] | [illegible] |
| 2 | [illegible] | 1 | [illegible] | [illegible] |
| 3 | [illegible] | 1 | [illegible] | [illegible] |
| 4 | [illegible] | 1 | [illegible] | [illegible] |
| 5 | [illegible] | 1 | [illegible] | [illegible] |
| 6 | [illegible] | 1 | [illegible] | [illegible] |
| 7 | [illegible] | 1 | [illegible] | [illegible] |
| 8 | [illegible] | 1 | [illegible] | [illegible] |
| 9 | [illegible] | 1 | [illegible] | [illegible] |
| 10 | [illegible] | 1 | [illegible] | [illegible] |
| 11 | [illegible] | 3 | [illegible] | [illegible] |
| 12 | [illegible] | 4, 11 | [illegible] | [illegible] |
| 13 | [illegible] | 11 | [illegible] | [illegible] |
| 14 | [illegible] | 11 | [illegible] | [illegible] |
| 15 | [illegible] | 11 | [illegible] | [illegible] |
| 16 | [illegible] | 11 | [illegible] | [illegible] |
| 17 | [illegible] | 11 | [illegible] | [illegible] |
| 18 | [illegible] | 18 | [illegible] | [illegible] |
| 19 | [illegible] | 1 | [illegible] | [illegible] |
| 20 | [illegible] | 11 | [illegible] | [illegible] |

Data item No. 20 (PRINT) contains the axial stations at which the output is to be printed. Data shall be calculated and reported for at least three axial stations as follows: (1) nozzle exit plane (zero feet aft), (2) 35 times RADJ, and (3) 50 times RADJ. Data may be calculated for additional axial stations in order to follow the course of reactions within the plume. Reactions are substantially completed at 35 times RADJ.

The Computer Program User's Manual should be consulted for additional information and for the complete description of the plume model computer program. The User's Manual has been published as Supplement 2 to AFAPL-TR-73-52.

89.0 Plume Model Output

At each axial station, as designated in the input data, the plume model computer program calculates various quantities related to mixing and reactions in the plume along the 11 stream tubes initially selected. In addition, at each station, the following overall or integrated values are calculated, and shall be reported:

| | |
|---|---|
| Total Flow, pps: | Gas Mixture, Fuel |
| Emission Indices, lb/1000 lb fuel: | CO, HC, $NO_x$ |
| Contaminant Flow, pps: | CO, HC, $NO_x$ |

The overall values shall be examined for internal consistency. The following criteria shall apply:

(a) Calculated fuel flow shall agree within ± 15% with the metered total engine fuel flow. If the agreement is not within 15%, then the plume model input data shall be reassessed. In particular, the curves of concentration versus radial location shall be examined to determine that the composition of the samples is representative of the actual local composition.

(b) Emission indices and contaminant flows at axial station 50 times RADJ shall be within 5% of the value calculated for axial stations 35 times RADJ. If such is not the case, the computer program shall be rerun for an axial station of 70 times RADJ.